INVESTIGATION OF THE EFFECT OF DIFFERENT FROTHER BLENDS ON THE FLOTATION OF SELECTED PGM BEARING ORES

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DECLARATION

I declare that this thesis, submitted for the degree of Master of Science in Engineering at the University of Cape Town, is my own work and has not been submitted prior to this for any degree at this university or any other institution.

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SYNOPSIS

Concentrators processing platinum group mineral (PGM) bearing ores use polysaccharide depressants to reduce the recovery of the naturally floatable gangue minerals (mainly silicates) present in the ores. Recent work has shown that high depressant dosage can completely depress the naturally floatable gangue from reporting to the concentrate. Unfortunately, this high dosage of depressant can have a negative effect on the recovery of valuable minerals present in the ore by reducing the stability of the froth.

In order to counterbalance the negative effects of depressant addition, frothers are normally added. The optimum frother provides a balance between the pulp kinetics and the froth recovery (through the effect of the frother on the bubble size and froth stability, respectively) over the range of frother addition. Usually one frother is added to accomplish this but using only one frother gives only one unique hydrodynamic relationship. It would be preferable to have independent control over the bubble size and froth stability, but unfortunately this cannot be achieved because changing the concentration of the frother changes both responses.

An alternative strategy for gaining more independent control over the froth characteristics and bubble size would be to use a blend of frothers, such as a weak and a stronger frother. Such a system would give an additional degree of freedom so that changing the ratio of the two frothers would provide more independent control of bubble Sauter mean diameter and froth stability. Little research work has been conducted on frother blends and none suggests the mechanism of blended frother action.

This study investigates through the use of batch flotation tests how blending low molecular weight alcohols with commercially available high molecular weight frothers impacts the solids and water recovery, as well as the valuable mineral recovery and concentrate grade, in different PGM ores. The results are compared with laboratory batch flotation tests using single frothers only. Two ores from the Merensky Reef in the Bushveld Igneous Complex, South Africa, were used .The frothers were selected to cover a range of polyglycols and alcohols, and included Senfroth 516, DOW 200 and DOW 250 (all polyglycols), and 1-butanol, 1-pentanol, 1-hexanol and MIBC (all low molecular weight alcohols). The frothers were used individually and as

blends at a total dosage of 50 g/t. Two phase tests were also carried out to measure the bubble sizes produced at different concentrations of both single frother and blends.

The results obtained from this study suggest that frother blends may have an implication in improving performance of a flotation circuit by independent control of bubble size, froth stability and solids holding capacity. A synergistic effect was observed with the use of the frother blends, resulting in enhanced performance compared to any of the frothers used individually.

Higher water and solids recoveries were obtained from tests using frother blends than from tests using the pure frothers. The highest solids and water recoveries were obtained when using the blends at ratios of 1:4 and 4:1, suggesting that the addition of small amounts of either frother to the other resulted in a synergistic effect. Higher amounts of water were recovered from tests using Merensky ore #2 than from tests using Merensky ore #1. This was attributed to differences in the mineralogy of the gangue minerals in the two ores resulting in differences in the mechanism of froth stabilisation.

The highest valuable mineral recoveries were achieved with the use of certain frother blends than with the pure frothers. The highest copper (>90%), nickel and sulphur recoveries were obtained from tests using blends of 10 g/t MIBC with 40 g/t of either Dow 200 or Dow 250.

This work has shown that there is scope for flotation concentrators to implement the use of a dual frother system in order to improve the performance of the circuit and that the addition of just a small amount of one type of frother to another is needed to bring about these enhancements.

The use of mixed frother blends can therefore be considered as a method for obtaining the improved performance for practical frother application. There is still a room for investigating the mechanisms at work when using frother blends, and extending the work to frother systems in which the two components are of opposite charge, that is, a mixture of cationic and anionic.

ABBREVIATIONS

AF	Aerofroths
Ca	Calcium
$Ca(NO_3)_2.4H_2O$	Calcium nitrate 4-hydrate
$CaCl_2$	Calcium chloride
C1	First concentrate
C2	Second concentrate
C3	Third concentrate
C4	Fourth concentrate
^oC	Degrees centigrade
CCC	Critical Coalescence Concentration
CMC	critical micelle concentration
CMR	Centre for Minerals Research
D_{32}	Sauter mean diameter
DF	Dowfroth
Cu	Copper
DFI	Dynamic Foamability Index
E_g	Gas holdup
g/t	Grams per ton
g/l	Grams per litre
g/mol	Grams
Guar	Guar gum
J_{wo}	Water overflow rate
kg	Kilograms
L/min	Litres per minute
Mg	Magnesium
$MgSO_4.7H_2O$	Magnesium sulfate heptahydrate
$Mg(NO_3).6H_2O$	Magnesium nitrate
MIBC	Methyl isobutyl carbinol
MnO_2	Manganese dioxide

mm	Millimetres
mv	Millivolts
m/v	Mass per volume
NaCl	Sodium chloride
Na_2CO_3	Sodium carbonate
NFG	Naturally floatable gangue
Ni	Nickel
nm	Nanometres
OH	Alcohols group
PAX	Potassium amyl xanthate
Pd	Palladium
PGM	Platinum group mineral
PGE	Platinum group element
ppm	Parts per million
PSD	Particle size distribution
QEMSCAN	Quantitative evaluation of minerals using scanning electron microscopy
rpm	Revolutions per minute
S	Sulphur
SF	Senfroth
SIBX	Sodium isobutyl xanthate
TEB	Tri-ethoxy-butane
TDS	Total dissolved solids
UCT	University of Cape Town
µm	Micrometre
wt%	Percentage by weight
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

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CHAPTER ONE
INTRODUCTION

1.1 Froth flotation

Froth flotation is the primary extraction process that is used for concentrating platinum group minerals (PGM) from the Merensky reef in South Africa. It is a physiochemical process that utilises differences in the surface properties of the valuable and gangue minerals, affecting their interaction at the air water interface. The more hydrophobic minerals attach preferentially to air bubbles; the loaded bubbles rise through the pulp to the froth region where the concentrate is removed for further processing. In the pulp phase the process is governed by the rate of bubble particle attachment. The size and number of bubbles present in the pulp phase is determined by both frother type and concentration together with the superficial gas flowrate.

Particles report to the froth phase by one of two mechanisms. The first is the selective recovery of hydrophobic particles by true flotation, as described. The second is unselective recovery by entrainment. Entrainment is the mechanism by which suspended particles within the pulp get trapped within the froth and remain unattached at the air water interface. Entrainment is mainly dependent on particle size, although particle density and shape can also affect the process. It also depends on froth stability.

Though widely used, flotation is an extremely complex, highly interactive process; this contributes to the difficulties experienced in optimising the recovery of PGM from their ores. Many of the fundamental aspects of the flotation process are still poorly understood. Klimpel (1984) divided the major variables in flotation into three main groups as shown in Figure 1.1. In addition to the physical parameters, the process chemistry used to treat ores is complicated, as many different reagents are usually added to the flotation system at various locations in the circuit. These reagents can interact with each other as well as with the ore, which makes the assessment of the effect of a reagent change on a flotation circuit of great importance.

1.1.1 Flotation reagents

Different chemical reagents are used in flotation to manipulate the surface properties of particles and create stable bubbles. Four main types of reagents are used: collectors, modifiers, depressants and frothers. Each has a specific purpose, although some reagents may have a dual purpose.

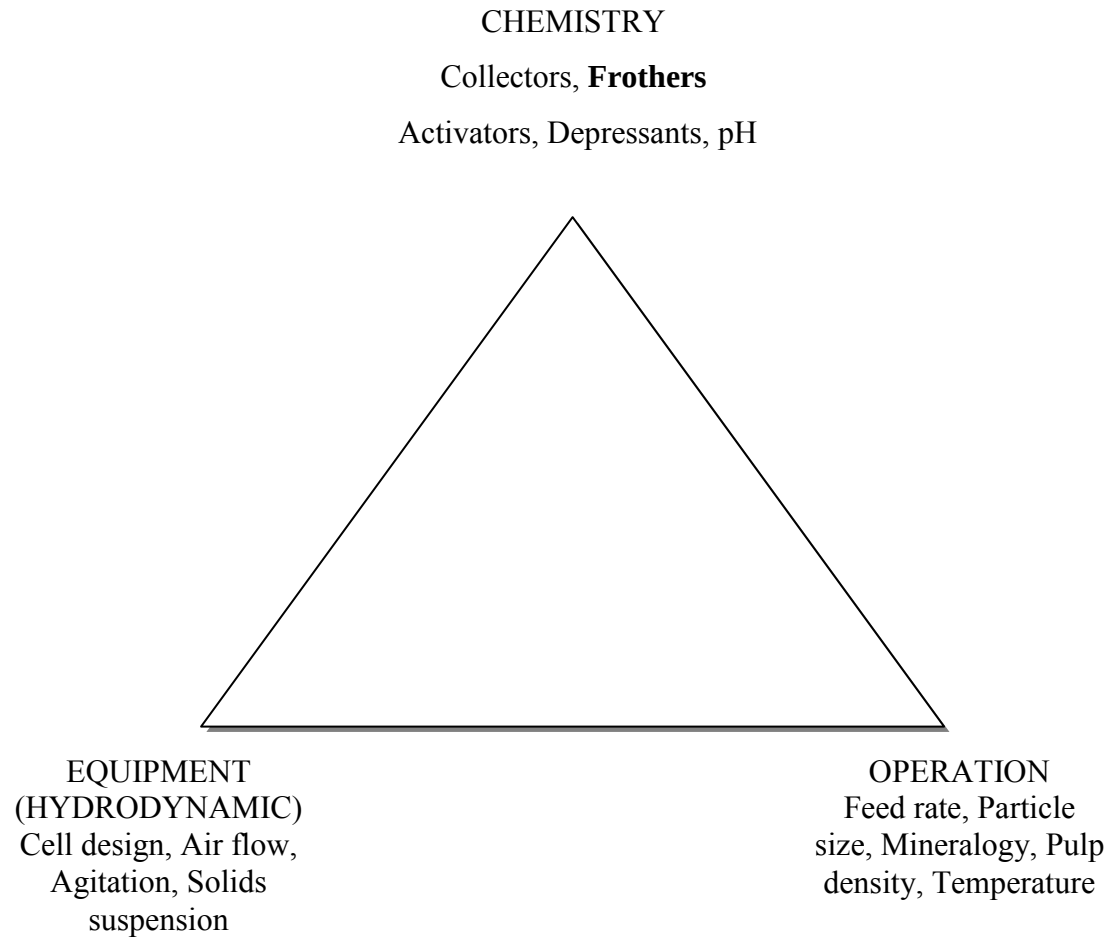

Figure1.1 Summary of variables in the flotation system (after Klimpel, 1984)

Collectors are surface active chemicals which selectively render the surface of minerals hydrophobic. This enables particles that contain these minerals to attach to bubbles. pH modifiers are used in certain conditions to modify the pH of the pulp so that the optimum

condition for collector adsorption will be achieved. They can also alter the chemical species present.

Depressants are normally added to alter the surface charge and chemisty of the gangue minerals in order to prevent them from reporting to the concentrate. Depressants selectively aggregate and/or render these minerals non-floatable, so as to hinder them from becoming attached to bubbles within the pulp phase. Examples of depressants are starch derivatives, guar gums, inorganic salts, carboxy-methylcellulose and polysaccharides. The choice of depressant depends on the gangue minerals present in the ore (Steenberg and Harris, 1984).

Frothers are heteropolar surface active compounds containing a polar group (hydrophilic) and a non polar group (hydrophobic), capable of adsorbing at the air water interface. The hydrophobic part is a hydrocarbon chain and the most common hydrophilic group is OH (as in alcohols) but can include alkoxy ($O–C_nH_{n+1}$) groups, as in polyglycols (Finch et al., 2008). Frothers help to establish the proper hydrodynamics within the pulp in the flotation cell (by controlling bubble size and gas hold-up) and to create a froth on top of the pulp that has the stability to hold the collected minerals, allow drainage of water and be mobile enough to be removed and then decay rapidly to assist downstream operations.

1.1.2 Frother types

Many frother types exist, of which the most common can be classified as alcohols, alkoxy-type frothers or polyglycol-type frothers (Laskowski, 1998). Alcohols and polyglycol-type frothers will be used in this study. The polyglycols are the strongest surface active frothers utilised. Examples of these are polypropylene glycol methyl ethers and the Dow frothers which are represented by the formulae $CH_3 – (O – C_2H_4)_n – OH$ and $CH_3 – (O – C_3H_6)_n – OH$. Alcohol frothers are mixtures of alcohols containing 5–8 carbon atoms. The best known frothers from this group are methyl isobutyl carbinol (MIBC) and 2-ethyl hexanol. They are regarded as highly selective frothers, less persistent and capable of maintaining small bubbles

1.1.3 Flotation of PGM bearing ore

Concentrators processing PGM bearing ores from the Merensky reef use polysaccharide depressants to reduce the recovery of the naturally floatable gangue (mainly silicate) minerals present in these ores (Steenberg and Harris, 1984; Bradshaw et al., 2004). Recent work at UCT has shown that the use of high depressant dosages has the undesirable effect of significantly

decreasing the stability of flotation froths, which can result in restricted mass pull and decreased valuable mineral recovery (Bradshaw et al., 2005). Using a single polyglycol ether type frother (Dow 200), Wiese et al. (2010) showed that an increase in frother dosage could overcome the destabilisation of the froth to a certain extent, and improve valuable mineral recovery, although this resulted in an increase in water recovery and dilution of the concentrate by entrained material. More recently, Wiese et al. (2012) found that using a stronger frother (Dow 250) in the presence of depressant, resulted in a more robust froth as shown in Figure 1.2.

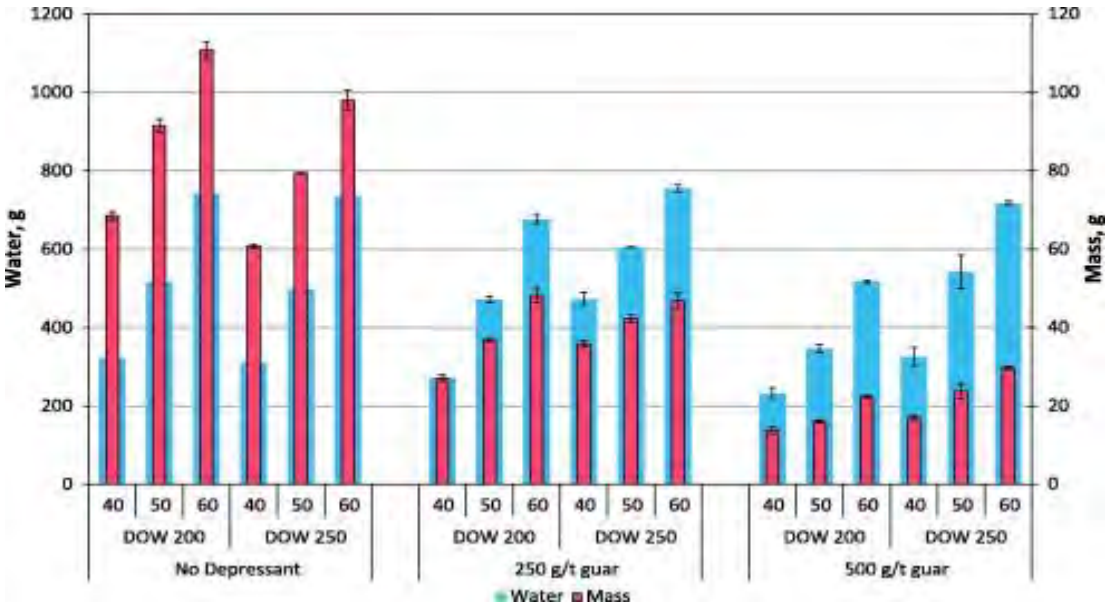

Figure 1.2 Final mass and water recovered using guar gum at dosages of 0, 250 and 500 g/t in the presence of Dow 200 and Dow 250 at dosages of 40, 50 and 60 g/t (from Wiese et al. 2012).

Another approach would be to use a blend of frothers, as suggested in section 1.1.4.

1.1.4 Frother blends

The ultimate goal of understanding the effects of flotation frothers in both pulp and froth zones is to increase the metallurgical performance in flotation circuits. In hydrodynamic terms, a good frother must give both the target bubble size in the pulp and adequate froth stability over a range of operating conditions. Frothers are often described as either weak (most alcohol) or strong (most polyglycol) frothers. In practice, frothers that are strong will introduce more water into the

froth and consequently be less selective due to increased entrainment. Weak frothers are more selective but with slow kinetics. An optimum frother type and dosage would provide a balance between kinetics and froth stability over the control range of addition. It is therefore important in every flotation circuit to find a suitable frother that will provide the right bubble size, froth stability and water drainage across a useful range of dosages and ore conditions. Frequently, this is difficult to achieve because changing the concentration of the frother changes both bubble sizes and froth stability. An alternative strategy for gaining more independent control over froth characteristics and bubble size might be to use a blend of frothers, such as a weak and a strong frother. Such a system would give an additional degree of freedom; changing the ratio of the two frothers would provide more independent control of Sauter mean bubble diameter and froth stability (Cappucitti and Nesset, 2009).

A dual frother system (i.e. weak/strong) could also be more cost effective since strong frothers normally function well at lower dosages. Recent studies by Zhang et al. (2012a) have shown that it is possible with a frother blend to have independent control over the water overflow rate, which is a measure of froth stability, and the two pulp hydrodynamic properties, Sauter mean bubble diameter and gas hold up. One of the impacts of frother blends on metallurgical performance was shown in the study by Hernandez-Aguilar et al. (2006) at the Lac des Iles palladium (Pd) operation in Canada. They postulated that an insufficient number of small bubbles in the plant cells was the main cause of the poor recovery of very fine Pd (less than 10 μm), as the plant operated with MIBC frother below the critical coalescence concentration (CCC). In an attempt to reduce the Sauter mean diameter, a blended alchohol-polyglycol frother was added to the same cells and successfully reduced the bubble size. As a result, the recovery of -10 μm Pd increased from below 20% to over 60%. This shows the impact that frother blends can have on the metallurgical performance of a circuit.

This thesis will investigate the impact of frother blends on the flotation of PGM bearing ores from the Merensky reef. This study will investigate whether blending frothers will improve the ability of these compounds to control the bubble size, and hence mineral particle recovery, as well as froth characteristics, as characterized by water recovery and entrainment. The study will concentrate on blending polyglycol and alcohol frothers in order to improve the flotation of platinum bearing minerals in Merensky ores.

1.2 Objective of the study

The overall objective of this study is to investigate the behaviour of frother blends in the flotation of platinum bearing ores. It is hypothesised that the blending of low molecular weight alcohol and polyglycol frothers will enhance the separate ability of these compounds to reduce bubble size and stabilize the froth, and hence improve mineral particle recovery.

1.3 Key questions

This investigation will focus on the following key questions:

1. What is the effect of different blends of low molecular weight alcohol and polyglycol frothers on solids and water recovery in PGM flotation compared to using the frothers on their own?
2. What is the effect of different blends of low molecular weight alcohol and polyglycol frothers on the concentrate grade and recovery of valuable minerals in PGM flotation compared to using the frothers on their own?
3. What is the effect of different blends of low molecular weight alcohol and polyglycol frothers on bubble size reduction and bubble size distribution compared to using the frothers on their own?

1.4 Scope of thesis

The thesis investigates the effects of using different blends of various low molecular weight alcohol and polyglycol frothers on solids and water recoveries, mineral recoveries and concentrate grades in the flotation of two different PGM bearing ores from the Merensky reef. Nickel, copper and sulphur recoveries are used as proxies for PGM recovery. A UCT technique is used to differentiate between entrained and floatable gangue recovered during batch flotation tests. The effect of the blends on the mean bubble size and the bubble size distribution is also investigated. All batch flotation tests are conducted in duplicate, to allow the calculation of the standard deviation between duplicate tests.

A schematic representing the parameters investigated in the study is shown in Figure 1.3. The chemical parameters are shown in blocks shaded in light blue, while the operational parameters are shown in blocks shaded in light green. Input and output variables are enclosed in the dashed red line. Because of cost and time constraints, the thesis does not include any analysis of PGMs.

1.5 Structure of the thesis

The thesis is organised into seven chapters. In chapter one, the flotation process is briefly introduced, with emphasis on the role of flotation reagents, particularly frothers. The importance of frother blends is discussed, as well as their proposed advantage in the flotation of PGM bearing ores. The objective and scope of the thesis are presented.

Chapter two is the literature review which describes the properties and roles of frothers in detail, and their effect on both the pulp and froth phases. It also shows their effect on bubble shape and size. Previous studies on the effect of frother blends on flotation are presented and discussed.

Chapter three describes the experimental equipment used in the thesis, the reagents employed in the batch flotation tests and the procedures used to perform the tests. The procedure for measuring bubble sizes is also presented.

Chapter four presents the results of the batch flotation experiments and the bubble size measurements.

In Chapter five, the results are discussed with special emphasis on the influence of frother blends on flotation performance.

Chapter six presents the conclusions drawn from the discussed results while Chapter seven provides recommendations from the study.

Raw data from all the experiments conducted are presented in the appendices.

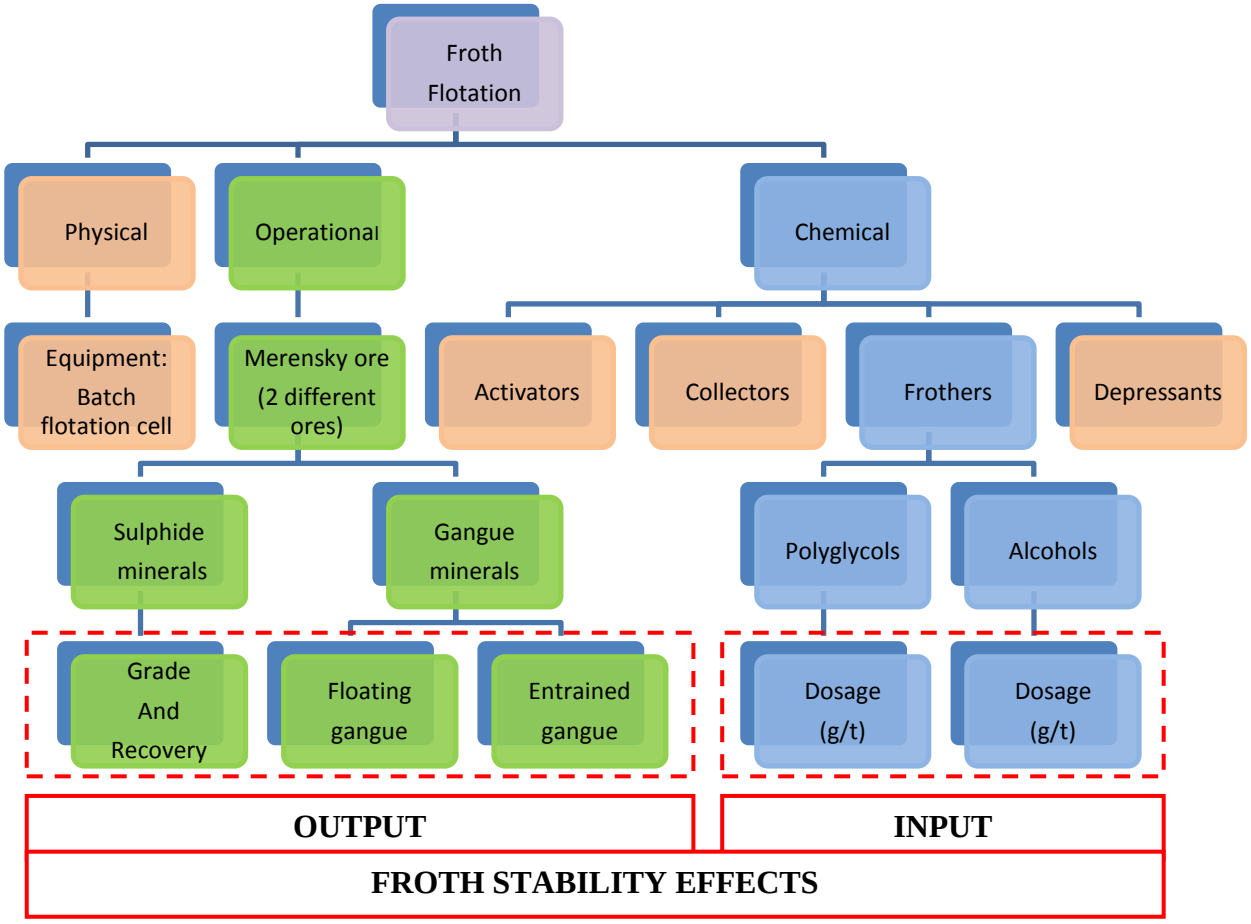

Figure 1.3 Schematic representation of the scope of the study

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction to flotation

Froth flotation is a physico-chemical separation process, used to extract valuable minerals from unwanted waste material (gangue). Flotation selectively exploits differences in the surface properties between minerals, separating particles based on differences in the ability of air bubbles to selectively adhere to specific mineral surfaces in mineral/water slurries. The particles with attached air bubbles are then carried to the froth where they can be collected as concentrate, while the particles that remain completely wetted stay in the pulp phase.

Froth flotation can be adapted to a broad range of mineral separations, as it is possible to use chemical reagents to selectively alter mineral surfaces so that they have the necessary properties for the separation. Flotation is currently in use for many diverse applications, with one example being separating sulfide minerals from silica gangue as practiced in the flotation of platinum bearing ores. The selection of chemical reagents to be used in flotation processes is of critical importance, as reagents manipulate the surface properties of particles and create stable bubbles.

This literature review focuses on the properties and uses of reagents, particularly frothers, and their role in the pulp and froth phases in a flotation cell. The use of frother blends in flotation, and their possible advantages, is also reviewed.

2.2 Flotation reagents

The properties of mineral particles in slurry are rarely suitable for froth flotation. Chemical reagents are therefore needed to control the relative hydrophobicities of the particles, and maintain the proper froth characteristics. Many different reagents are involved in the froth flotation process, with the selection of reagents depending on the specific ore type being treated. Four main types of reagents are used in the flotation of platinum bearing ores, each for a specific purpose, although some reagents may have a dual purpose.

2.2.1 Collectors

Collectors are reagents that are used to selectively adsorb onto the surfaces of particles. They are surface active chemicals which selectively render the surface of minerals hydrophobic. This

enables particles that contain these minerals to attach to bubbles. They form a layer on the particle surface that essentially makes a thin film of non-polar hydrophobic hydrocarbons. The collectors greatly increase the contact angle so that air bubbles will adhere to the surface. The selection of the correct collector is critical for an effective separation by froth flotation. Collectors can be generally classed according to their ionic charge: they can be nonionic, anionic, or cationic. The most widely used collectors in the recovery of sulphide minerals belong to the following general chemical families: monothiophosphates, dithiophosphates, thionocarbamates, thioureas, alkyl-xanthate esters, xanthogen formates, mercaptobenzothiazole and xanthates (Day, 2002). Xanthates are most widely used in the flotation of PGM bearing ores.

2.2.2 Depressants

In the flotation of platinum bearing ores, polysaccharide depressants are used to reduce the recovery of the naturally floatable gangue minerals. These depressants are either modified guar gum or carboxymethyl cellulose. Depressants selectively aggregate and/or render these minerals non-floatable, so as to prevent them from becoming attached to bubbles within the pulp phase.

2.2.3 Activators

Activators are used under certain conditions to enhance collector adsorption. Care is taken when selecting activators so as not to activate gangue minerals, as collector adsorption onto gangue is detrimental to the process performance.

2.2.4 Frothers

Frothers are heteropolar surface active compounds containing a polar group and a hydrocarbon radical capable of adsorbing at the air-water interface. They lower the surface tension of the water, and create conditions for froth formation. The frother molecules effectively form an envelope around the bubbles, which inhibits bubble coalescence. Many frother types exist, of which the most common can be classified as alcohols, alkoxy-type frothers or polyglycol-type frothers (Laskowski, 1998). Due to their importance in this study, frothers are discussed further.

2.3 Flotation frothers and their properties

Frothers have been classified in different ways in literature. In one classification by Dudenkov and Galikov (1969), frothers are classified as acidic, basic and neutral. The neutral frothers are widely used in the flotation of base-metal ores, oxide minerals and industrial minerals. They

function in both acidic and alkaline media. Frothers generally contain a polar (hydrophilic) and a non-polar (hydrophobic) group, capable of absorbing at the water–air interface. The hydrophobic part is a hydrocarbon chain and the most common hydrophilic group is OH (as in alcohols) but can include alkoxy ($O–C_nH_{n+1}$) groups, as in polyglycols (Finch et al., 2008). The frother molecules are arranged at the air–water interface such that hydrophilic or polar groups are oriented into the water phase and the hydrophobic or nonpolar hydrocarbon chain into the air phase. Figure 2.1 shows the orientation of frother molecules on the surface of air bubbles.

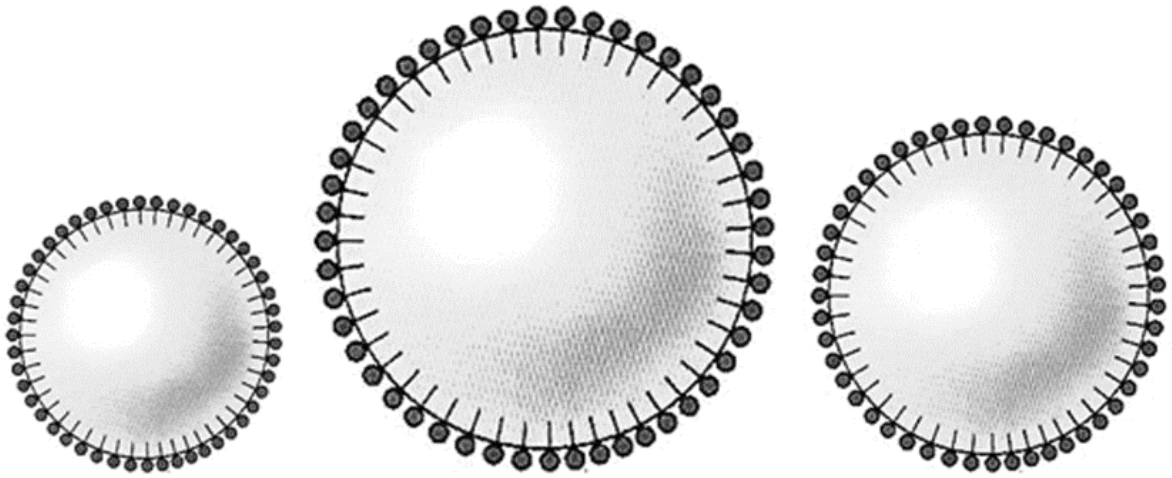

Figure 2.1 Orientation of the frother molecules in the surface of bubbles (Khoshdast and Sam, 2011)

Cappuccitti and Finch (2008) provided a list of the most widely used commercial frothers which include:

(a) Natural oils such as terpineol (as in pine oil) and cresols

(b) C5–C8 aliphatic alcohols

(c) Polypropylene glycols and their alkyl ethers

(d) Mixed ethers, aldehydes and ketone co-products of oxo-alcohol production

(e) Alkoxy-alkanes such as TEB (tri-ethoxy-butane)

The aliphatic alcohol frothers together with polypropylene glycols and their alkyl ethers (hereby commonly referred to as polyglycol frothers) will be used in this study and are discussed further.

2.3.1 Polyglycols

The polyglycols are the strongest surface active frothers utilised. The common group of polyglycols includes polypropylene glycol methyl ethers represented by the formula CH_3 - (O-C_3H_6)n-OH and the polypropylene glycols represented by the formula H-(O-C_3H_6)n-OH (Klimpel and Isherwood, 1991). They are completely miscible in water, and produce compact, lasting froth structures that break down readily in the launders (Crozier, 1992). The polyglycols produce more stable and viscous froths compared to alcohol frothers, which helps promote the recovery of coarse particles in the flotation feed.

Various polyglycol ethers are produced under different trade names by the different reagent manufacturers, such as the Dow Chemical Company (Dowfroths, DF#), Union Carbide (Ucon frothers), Cyanamid (Aerofroths, AF#), ICI (Tecfroths) and Senmin (Senfroths ,SF#). The Dowfroths are usually methoxy polypropylene glycols which include the most common flotation frothers Dow 200 [$CH_3(O\text{-}C_3H_6)_3OH$], Dow 250 [$CH_3(O\text{-}C_3H_6)_4OH$] and Dow 1012 [$CH_3(O\text{-}C_3H_6)_{6.3}OH$] (Khoshdast and Sam, 2011). The molecular weight and carbon length of polyglycol ether frothers normally determine their power and performance (Laskowski et al., 2003). A higher molecular weight frother gives a more persistent and less selective froth than a lower molecular weight frother.

2.3.2 Aliphatic alcohols

These frothers are mixtures of alcohols containing 5–8 carbon atoms. The best known frothers from this group are methyl isobutyl carbinol (MIBC) and 2-ethyl hexanol. Aliphatic alcohol frothers are used as mixtures of different carbon lengths and as a mixture of hydrocarbon oils (Bulatovic, 2007). Figure 2.2 shows general structure of different alcohol frothers. Aliphatic alcohol frothers are known to show less tenacity, decrease water retention and produce more brittle froths than the polyglycols. They have relatively low water solubility and are highly selective in the flotation of fine to medium particle sizes when used at low to moderate dosage at higher pH (Klimpel and Isherwood, 1991). Klimpel and Isherwood (1991) have shown that, for most of the aliphatic alcohols frothers, increasing the frother dosage can improve the recovery of large particles.

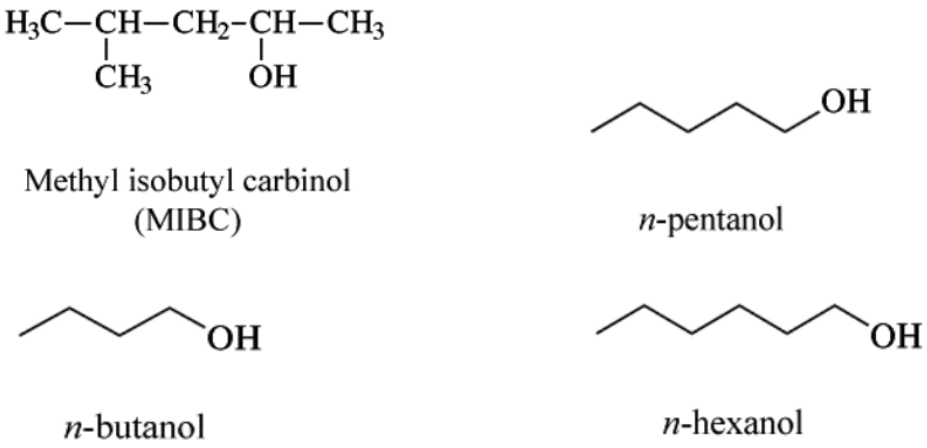

Figure 2.2 Chemical structures of aliphatic alcohols

However the economics become less desirable and there are usually selectivity problems in the circuit with the consequence that the overall rate of recovery consequently starts to drop. This indicates that there is always a practical operable range for a given frother in a flotation circuit beyond which undesirable events start to occur.

2.4 Roles of frothers in flotation

Flotation frothers are widely acknowledged for the important roles they play in the flotation process, particularly in terms of their roles with respect to limiting the bubble size, and controlling the stability and mobility of the froth phase. These factors play a significant part in the overall recovery and grade that can be achieved from a flotation cell (Comley et al., 2002). In addition to the formation of froth, frothers have a considerable effect on increasing the air dispersion in the flotation machine, reducing the coalescence of individual bubbles in the pulp phase and decreasing the rate at which the bubbles rise to the surface (Acuna and Finch (2010); Rafiei et al., 2011). Frothers increase the strength of the bubbles and the stability of the froth that is formed as a result of mineralized air bubbles ascending to the surface of the pulp.

The frothing ability of frothers in aqueous solution is thought to be connected to a decrease in the surface tension. However, it is understood that the best foaming agents are not necessarily the best flotation frothers and the importance of the interaction of frothers and collectors in particle bubble attachment cannot be ignored (Crozier,1992). In general, the flotation selectivity of surface active frothers is not high, which makes frother selection in flotation practice quite

difficult, especially when a large number of factors influence the action of a frother and froth stability in general. The addition of flotation frothers is common in mineral processing plants except in operations where high salt levels in the process water can substitute the prime functions of the frother (Quinn et al., 2007). They help in maintaining fine bubble sizes, whereby the dispersion of air in the flotation cell also improves (Nesset et al., 2006).

2.4.1 Effect on bubble size and velocity

The role of frothers in reducing the bubble size has acquired more attention in recent times. On the practical side, arguments are made that the bubble size is a key driver through its contribution to bubble surface area flux, and hence flotation kinetics (Gorain et al., 1997; Hernandez et al., 2003). An argument in favour of this position is the metallurgical success of gas velocity profiling (distributing the air in an organized way down a bank of cells) which emphasizes the management of the gas dispersion conditions in the pulp phase (Cooper et al., 2004; Gorain, 2005; Hernandez-Aguilar and Reddick, 2007)

Both frother type and concentration have great impact on bubble properties (Cho and Laskowski, 2002; Finch et al., 2008). Being surface active agents, frothers will concentrate at the air-water interface and impact interfacial properties of the bubble. Frothers help in the formation of small bubble size and hence increase the surface area on the bubbles created in the pulp. In the pulp this mechanism appears to have at least two components: bubble break up and bubble coalescence. In an initial bubble formed in water under certain levels of turbulence, the presence of frother will contribute to the ability of the bubble to break into smaller bubbles and will also affect the ability of the resulting daughter bubbles to combine into larger bubbles (Nesset et al., 2006).

The mechanism by which frother controls bubble size is not clearly understood. It is not directly related to surface tension reduction (Grau and Laskowski, 2006). Finch et al. (2008) proposed an explanation that lies in the dynamic nature of the surface forces caused by uneven concentrations of frother over the bubble surface at the moment of air injection into the solution where frother is randomly distributed. It is thought that the force resulting from the surface tension gradients, rather than an overall decrease in surface tension itself, would produce surface instabilities that result in bubble break up when sufficient mechanical energy (turbulence) is introduced in the system.

Figure 2.3 (Nesset et al., 2006) shows the significant impact of frother addition on the size of bubbles in the air-water system. It shows that the Sauter mean diameter (D_{32}) decreases rapidly to a limiting minimum size, while the initially bi-modal shape of the frequency distribution of bubble size population becomes progressively unimodal, finer and narrower. The frother concentration at which the minimum mean diameter is reached has been termed the "critical coalescence concentration" or CCC (Laskowski et al., 2003). The dependence on concentration is similar regardless of frother type. The same test program revealed that impeller speed, spanning the practical operating range, had no marked effect on reducing bubble size, despite more than doubling the tip speed (from 4.6 to 9.2 m/s, representing an eight-fold increase in energy input). The combined outcome is remarkable both by what it shows is not important, increased energy input, and what is important, the presence of frother, even at very low concentrations. Harris (1976) made a similar observation. This shows the over-riding importance of frother in controlling bubble size.

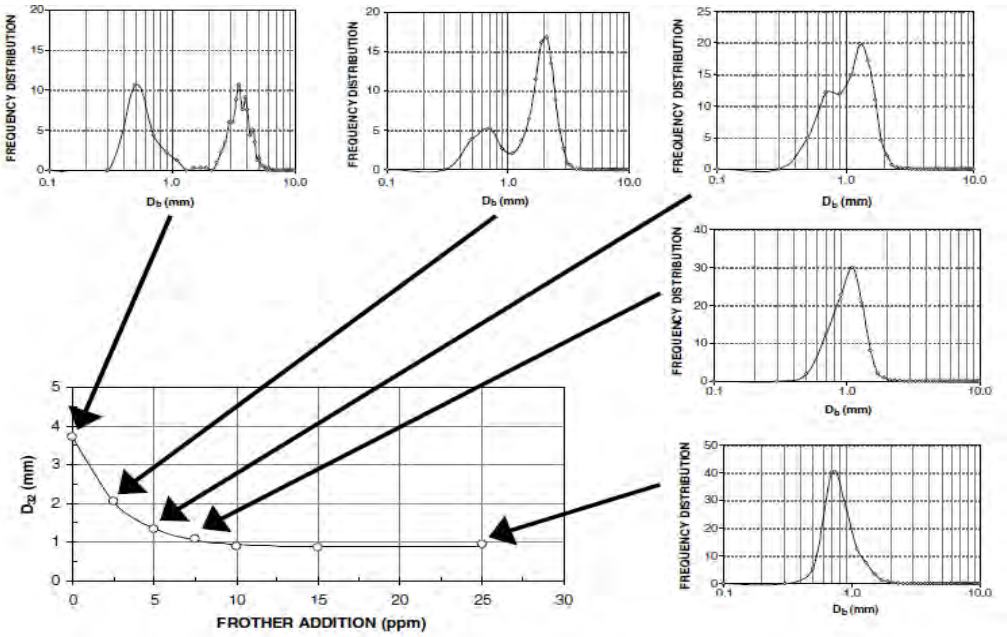

Figure 2.3 Impact on bubble size distribution and Sauter mean size (D_{32}) as frother concentration is increased (DF-250) and Jg = 0.5cm/s) (Nesset et al., 2006)

Sauter mean diameter can also be predicted from hydrophile-lipophile balance (HLB) values. HLB is a measure of the solubility of a frother in water, and is calculated based on the number of hydrophile (polar) and lipophile (non-polar) groups in the molecule (Laskowski, 1998). Zhang et al. (2012b) established a correlation between CCC and HLB in a step towards predicting bubble

size in flotation systems from frother structure for commercial frothers. They developed a methodology to characterize frothers by relating the impact on bubble size reduction represented by the CCC to the frother structure represented by the HLB. A number of frothers were tested from aliphatic alcohol and polyglycol families, covering a range in alkyl groups represented by 'n', the number of carbon atoms, and the number of propylene oxide groups represented by 'm'. The Sauter mean diameters (D_{32}) were derived from bubble size distributions measured in a 0.8 m^3 mechanical flotation cell. The D_{32} *vs.* concentration data were fitted to a 3-parameter model to determine CCC95, the concentration giving 95% reduction in bubble size compared to water only. The result showed a series of self-similar CCC95-HLB trends dependent on 'n' and 'm'. Figure 2.4 a shows the CCC95-HLB relationship for the aliphatic alcohols from their study. Starting with propanol, there was a decrease in CCC95 as HLB decreases. Commercial frother FX120-01 was seen to fit the trend. For C < 6 there was an increasing isomer effect which is illustrated by comparing hexanol and [pentanol isomers in Figure 2.4 b.

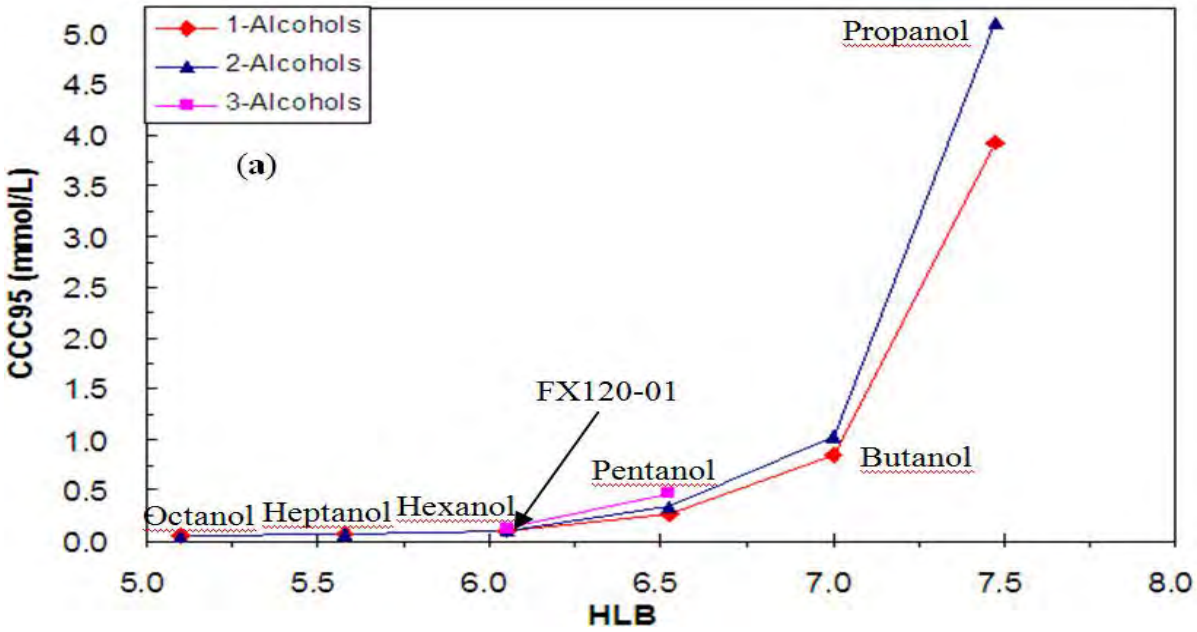

Figure 2.4 (a) CCC95 versus HLB for the aliphatic alcohols and their isomers (Zhang et al., 2012b)

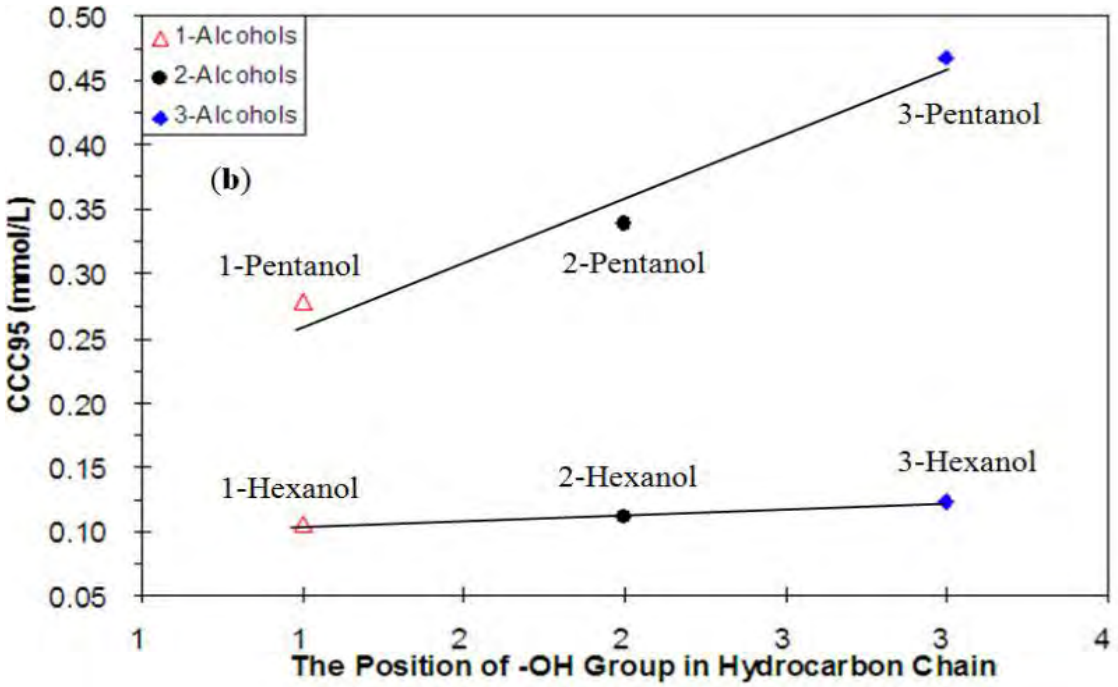

Figure 2.4 (b) The effect of –OH group position on CCC95 for pentanol and hexanol isomers (Zhang et al., 2012b)

Figure 2.5 shows CCC95 *vs.* HLB for the two polyglycol families as a function of 'm' for a given 'n'. CCC95 decreases with increasing 'm' in a series of parallel plots which trend to lower HLB with increasing 'n'. The commercial frothers are shown to fit the pattern.

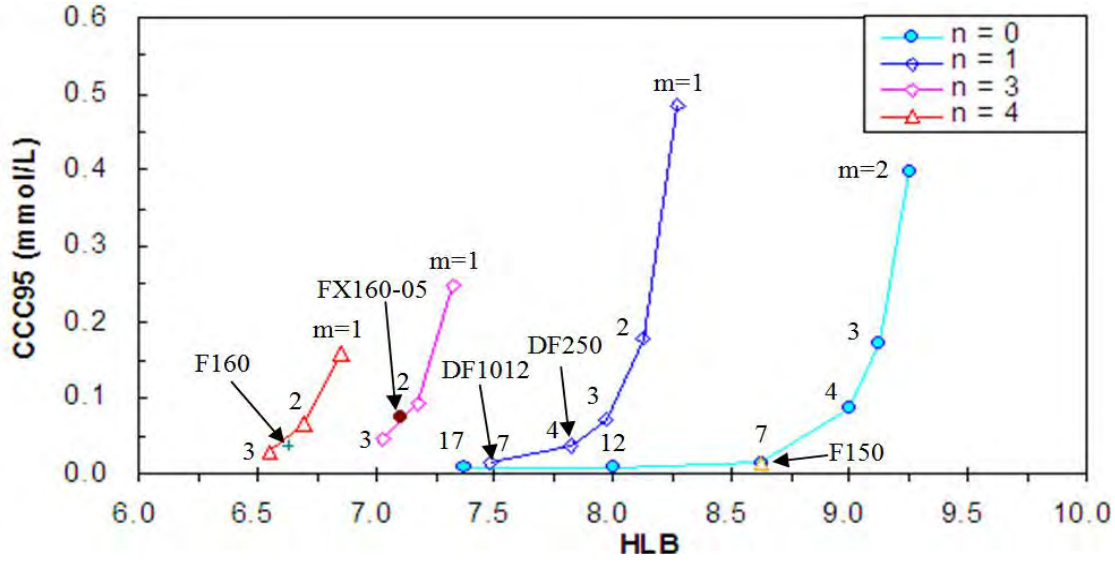

Figure 2.5 CCC95 versus HLB for the polyglycols as function of 'm' and 'n' (Zhang et al., 2012b)

Zhang et al. (2012b) also developed empirical models for the polyglycols and 1-alcohols showing that CCC95 could be predicted knowing ‘n’ and ‘m’, and that Sauter mean bubble size could also be predicted.

A study conducted by Azgomi et al. (2006) compared the gas hold up at various concentrations of different frothers that included alcohols like 1-pentanol, 1-hexanol, MIBC, 1-octanol and a polyglycol F150. It was observed, as seen in Figure 2.6, that at higher concentration of frother beyond the CCC, the gas hold up increased steadily. The conclusion was that the bubble size population becomes finer, meaning that the bubble size continues to decrease above the CCC.

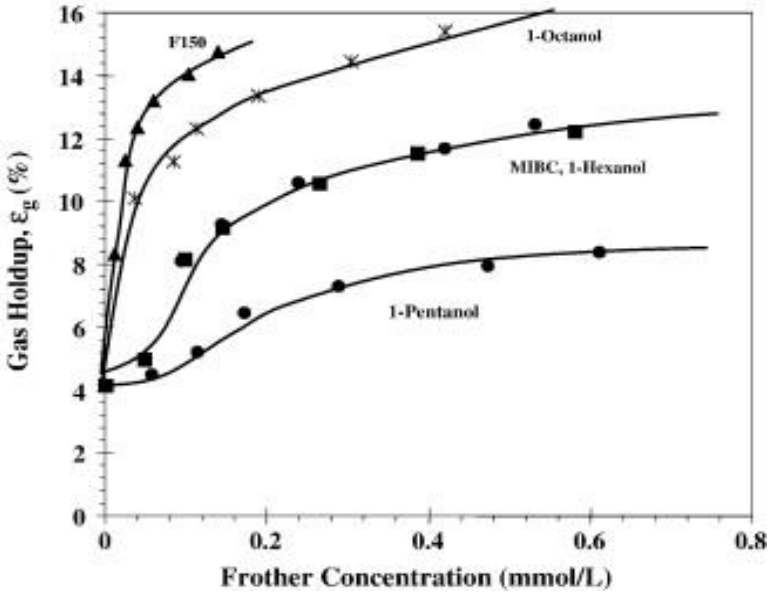

Figure 2.6 Comparing gas hold up vs. concentration for five different frothers (Azgomi et al., 2006).

In a follow-up study, Azgomi et al. (2007) measured bubble sizes for the same frothers at constant gas hold up. As can be seen in Figure 2.7, different frothers produced different bubble sizes at the same gas hold up. It was observed in this situation that pentanol produced fine bubbles which rose with little retardation compared to F150 which could not produce such small bubbles but introduced significant retardation. This means that pentanol is a stronger frother with regard to bubble size reduction, whereas the polyglycol acts as a stronger frother when it comes to retarding bubble rise velocity.

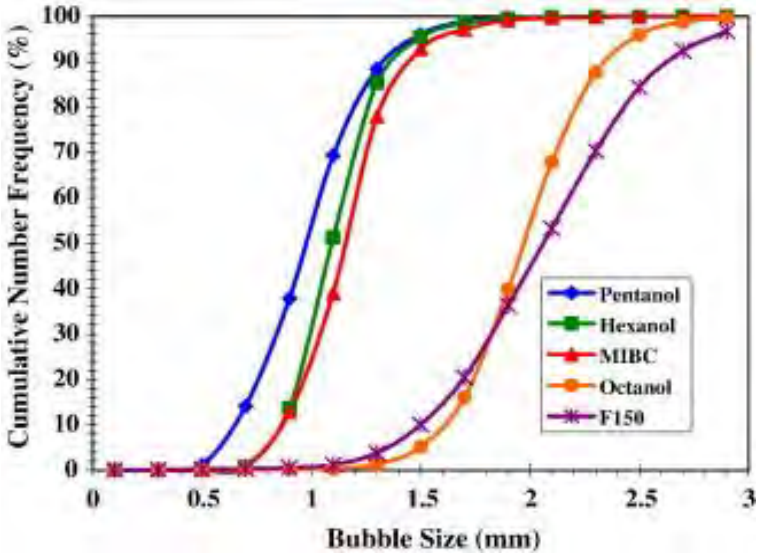

Figure 2.7 Cumulative number frequencies for the five frothers at 6% gas holdup (Azgomi et al., 2007)

2.4.2 Effect on pulp phase

Frothers help to establish a proper environment in the pulp for the attachment of mineral particles to bubbles. The physical environment of the pulp must be such that particles collide frequently with bubbles. It must not be too turbulent or the bubble-particle aggregates will be broken. In addition, the bubbles formed must be of a size large enough to provide sufficient buoyancy to transport the particles to the interface, but small enough to create a large surface area per unit volume of gas in the cell. The chemistry of the pulp must be such that the valuable minerals adhere to the bubbles as they collide, and are amenable to flotation. A successful frother must allow sufficient thinning of the liquid film between the colliding bubble and particle so that attachment can take place in a time frame of the collision. However, thinner liquid films enhance bubble–bubble coalescence (Gupta et al., 2007). Therefore a successful frother must achieve a delicate balance between these two competing processes and provide adequate stability of the bubble/particle moiety, and at the same time allow the weakly adhering or mechanically trapped particles to escape. Particle and bubble behaviour in the pulp are discussed in the following sections.

2.4.2.1 Particle behaviour

In order for a mineral particle to float it must successfully attach to an air bubble and rise up through the pulp phase and into the froth. The behaviour of particles within the pulp is such that the size of both particles and bubbles influence the probability of a bubble-particle collision. In a

model developed by Schuhmann (1942) to describe the flotation rate based upon the collisions between particles and bubbles, the key factors are the collision probability, the induction time and the stability of the bubble- particle aggregate. The collision probability is influenced by the number, size and velocity of the bubbles, together with the size, shape and concentration of the particles. The induction time is the time taken for a particle that has collided with a bubble to attach to the bubble.

The hydrophobicity of the particle influences the time taken for a stable bubble particle aggregate to form. The likelihood that the aggregate will remain stable and rise into the froth is dependent on both the hydrophobicity and size of the particle. It is known that collectors improve kinetics of the bubble-particle attachment process. In a study performed by Laskowski (1974) it was shown that the induction time required for bubble-particle attachment also varies with frother concentration. Combinations of factors contribute to this, including slow bubble rise velocity due to particle weight and larger particles having a lower attachment stability, which makes them more susceptible to detachment. Thus, an optimum particle size exists at which maximum attachment occurs within the pulp.

In addition to hydrophobicity, it was shown in the study conducted by Koh et al. (2009) that particle shape also plays a role in determining the particle floatability. Most of the work that has been conducted on particle recovery in the pulp also indicates that there is a need to have bubbles with size and speed that can be able to recover particles with a variety of sizes and shapes (Bulatovic, 2007). For different single frothers used, each was shown to have a different induction time.

2.4.2.2 Bubble formation and behaviour in pulp

It is important to understand the formation and behaviour of bubbles in the pulp because the number and size of the bubbles within the pulp affect the probability of bubble-particle collision.

Surface tension was considered the most determining factor in bubble size formation until Sweet et al. (1997) showed that significant variation in bubble size occurred over an insignificant change in surface tension. Subsequently, Grau and Laskowski (2006) showed that the dynamics of frother adsorption control pulp bubble size.

Experimental work has shown that, in the presence of frothers, the size of bubbles in the flotation system can decrease significantly (Cho and Laskowski, 2002; Melo and Laskowski, 2006; Finch et al., 2008). This may result from two related actions: improvement in air dispersion due to formation of small bubbles and deterioration in the coalescence of air bubbles in the pulp. Both actions affect froth formation and bubble transport to the froth zone. In the absence of frother on the bubble surface, the coalescence of bubbles takes place instantaneously. In the presence of a frother, however, the coalescence of bubbles occurs at a longer distance than in the absence of frother. Molecules of the frother usually adsorb on air bubbles, thus increasing the stability of the hydrated layer surrounding the bubble (Finch et al., 2006). The hydrophilic groups of adsorbed frothers are directed to the liquid phase and actively interact with molecules of water. This in fact leads to an increase in the mechanical strength of the envelope surrounding the bubbles and prevents destruction or collision with other bubbles (Bulatovic, 2007). It has been determined that a single frother may effectively prevent coalescence only when the air bubbles do not differ appreciably in their size. The coalescence of bubbles possessing large differences in diameter is highly pronounced (Grau and Heinskanen, 2005).

It is currently clear that the frother inhibits further break up and coalescence of the generated bubbles; the fundamental explanation for this observation has not been fully understood. Finch et al. (2008) demonstrated that molecules of surface-active agents, which adsorb on the surface of bubbles, are shifted to the bottom portion of the air bubble during their upward movement in the liquid or pulp. This results in lowering the surface tension in this region, creating a difference in the surface tension between the upper and lower regions of the bubble. It has been thought since then that the force resulting from the surface tension gradients, rather than an overall decrease in surface tension itself, would produce surface instabilities that result in bubble break up when sufficient mechanical energy (turbulence) is introduced in the system.

Along the surface of the air bubble, a force is created which attempts to equalize the surface tension to prevent further shifting of frother molecules to the lower portion of the bubble. This force hinders the motion of the molecules on the surface of the air bubble, thus lowering the mobility of the bubble. The decrease in mobility makes the bubble behave like a solid sphere (Clift et al., 2005). The decrease in the velocity of the air bubble due to the surface-active agent

is evident (Kracht and Finch, 2010). The slow rise velocity of bubble from the pulp to froth is of particular importance to allow enough time for the hydrophobic particles to attach to the bubble.

From the research work reviewed, the behaviour of the bubbles in the pulp is still not well understood. Frothers reduce the size of generated bubbles to a minimum at the CCC, above which no further bubble size reduction takes place. But as we have seen previously in section 2.4.1, bubble sizes can still decrease after CCC, and each frother type produces a different bubble rise velocity from pulp to the froth. A need still therefore exists to explore the effect of flotation frothers on bubble behaviour.

2.4.3 Effect on froth zone

The behaviour of the froth is usually said to be one of the most important aspects in flotation. The froth zone provides the environment for the separation of the valuable minerals from the gangue, allowing drainage of the entrained material back into the pulp. The froth phase must be stable enough to allow unwanted material to drain out of the froth while the desired minerals are transported to the concentrate launder. When the froth is not stable enough, the mineralized bubbles rupture before collection; when the froth is too stable, not enough drainage occurs and the water and gangue recoveries are too high. At the same time, the froth must not be so stable that it does not break down when it reaches the launder, which could cause problems in subsequent processes (Cappuccitti and Finch, 2008). Various factors including the type and concentration of the frother as well as the properties of the particles in the froth affect its stability (Harris, 1982).

2.4.3.1 Froth Structure

At the pulp-froth interface, when the bubbles are of similar sizes in mono-disperse systems, they generally pack using optimal packing such as hexagonal close packing. As layers of bubbles accumulate, water drains from between the bubbles and polyhedral structures develop. Generally, large bubbles deform readily, while smaller bubbles are able to retain a spherical shape.

Most of the processes that occur in the froth are directed toward froth breakage. It is considered that a stable system can only be accomplished in the case of complete separation of the system into two phases (i.e. liquid and gas). At the moment of froth formation, the air bubbles are separated by a thick film of liquid. According to Finch et al. (2006), the bubbles formed in the

presence of frother are surrounded by a region of organised water and this bound water may be sufficient to hinder the drainage of the water film between adjacent bubbles and prevent coalescence. The frother may be considered to have conditioned the water to become an anti-coalescence medium by altering local bulk water properties.

The drainage of water from froth occurs in the initial seconds in the case of unstable froth. The water drains under the influence of gravity, although other factors (e.g. pressure and difference in capillary pressure) are also important. The thickness of the solvated water envelopes also strongly affects the drainage of water. The greater the hydration of the capillaries, the more slowly the water drains.

The drainage of liquid from planar boundaries in fine bubble froth is low. This is due to the fact that a small air bubble in the froth has more uniform surface curvature and, consequently, the difference in local film pressure is smaller (Bulatovic, 2007). Very small bubbles remain spherical and the froth retains a lot of water, even with the densest packing. According to this, for a froth to have an optimum stability, there has to be an optimum size of air bubbles.

Frothers play the role of stabilizing the film around the bubbles. The heteropolar frother molecules orient themselves in the adsorbed layer with their polar groups directed toward the liquid phase. The polar group undergoes strong hydration and forms a base of thick hydrated layer on the water surface. The hydrated layer of uniformly oriented molecules exhibits strong resistance to destruction. The hydrated layer of the surface films in the froth plays an important role, not only in the attachment of mineral particles to bubble, but also in determining the stability of the froth. A sequence of photographs showing a gradual transition of structure from that of non-drained foam with spherical bubbles to relatively well-drained foam with polyhedral bubbles separated by very thin lamellae was provided by Kitchener and Cooper (1959). Figure 2.8 shows this structural foam transition.

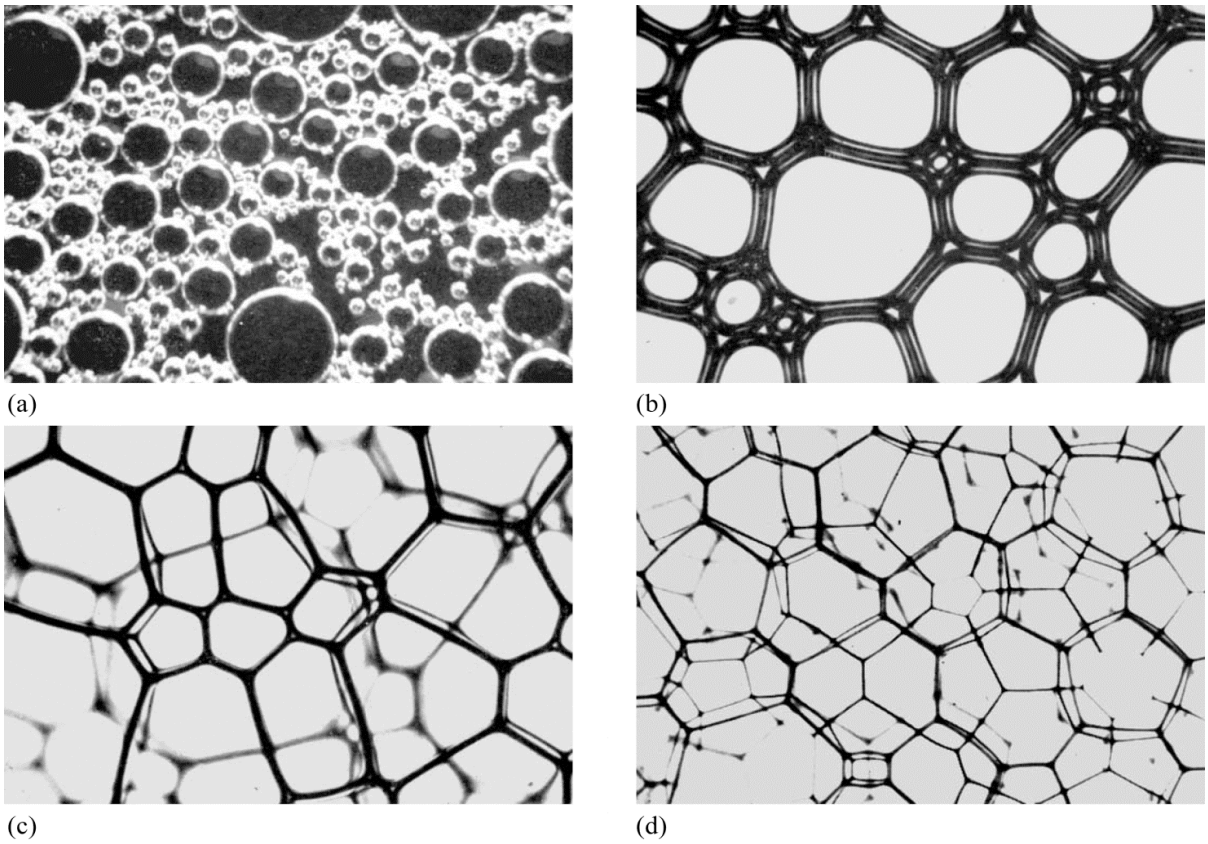

Figure 2.8 Photomicrographs showing foam transition: (a) a non-drained spherical bubble foam (b) a partially-drained foam, showing distortion of bubbles; (c) after further drainage, the lamellae and Plateau borders continue to thin; and (d) a well-drained foam, showing polyhedral cells and very thin Plateau borders (Kitchener and Cooper,1959)

Froth stability is therefore a key parameter that influences flotation performance (Ventura-Medina et al., 2003). In the three phase system, froth stability is generally controlled by the attached solids and the chemistry of the solution.

In two phase systems, frothers have been classified qualitatively as ‘powerful’ or ‘selective’. Laskowski et al. (2003) proposed the use of a comparison between the CCC and the dynamic foamability index (DFI) to quantitatively classify frothers in terms of their strength and selectivity. DFI is defined as the limiting slope of the retention time–concentration curve as the frother concentration approaches zero (Harris, 1982). In a corresponding study, Melo and Laskowski (2006) showed that the flotation rate constant for the recovery of water correlates well with CCC and DFI data. Cappuccitti and Nesset (2009) developed an alternative method to classify the strength of frothers based upon the relationship between the equilibrium two-phase foam height and the gas holdup in the pulp.

For the three phase system, together with frother type and concentration, solid particles affect the froth stability characteristics within froth. The effects of attached particles on froth stability are fairly well understood. Particle hydrophobicity, state of aggregation, bubble loading, particle size and shape are all known to affect froth stability.

It has been widely published in the literature that the presence of hydrophobic particles increases the stabilising effect of particles on the froth. However, once a 'critical' hydrophobicity is reached, highly hydrophobic particles start to destabilise the froth (Ata et al., 2003).

There is an optimum concentration of frother at which the most stable froth is obtained. Excess frother leads to a decrease in froth stability and may even suppress the froth completely (Gelinas et al., 2005). This is explained by the fact that high frother concentration strongly decreases the surface tension of the solution; thus the condition for the formation of a sufficiently stable hydrated layer deteriorates.

It has been suggested that a combination of several surface active agents is quite effective in controlling and regulating froth properties (Hernandez-Aguilar et al., 2006). The stability of the two-phase froth also depends on the characteristic size of the air bubbles. The stability of the froth is decreased if the adjoining bubbles differ in size. This is due to a large difference in their capillary pressure.

2.4.3.2 Particle behaviour

There is much argument in the flotation literature concerning the role of particles on froth properties. The presence of particles in the froth may improve the stability of the froth or may have a negative effect. Isolated hydrophobic particles may induce coalescence (Dippenaar, 1982) but particle-laden bubbles, as in flotation, tend to promote froth stability (Rao and Leja, 2004). The nature of the system (particle size, bubble loading, collector type, ionic content in the water) can be expected to have a role but, in general, froth stability is anticipated to increase in the presence of floatable solids (Kuan and Finch, 2010).

From the research performed on the factors affecting froth stability, it is clear that particles play a big role but more complexity arises given that particles within froth are mobile and the distribution of attached particles changes due to processes such as particle attachment and detachment in the froth. Ata (2009) has shown that particle detachment occurs between two

coalescing bubbles. Factors behind the rate of detachment have been known to be particle size and collector concentration. From the observations of detachment occurring within the bulk of the froth phase, Neethling and Cilliers (2002) suggested that the rate of solids re-attachment within froth is low, as the air-water interfacial area in the Plateau borders is small and likely to be saturated.

The Merensky reef consists of a pegmatoidal pyroxenitic layer lying between two thin chromitite layers. The pyroxenite layer varies in thickness across the Merensky Reef. The Merensky reef is known to vary, with various forms of alteration, depending on where the ore is mined (Brough, 2008; Wiese, 2009). The base metal sulfide content of the Merensky reef is in the region of 1%. The major base metal sulfide is typically pyrrhotite at levels of approximately 45%, followed by pentlandite at approximately 32% and chalcopyrite at approximately 16% (Liddell et al., 1986). The PGM in the Merensky reef are strongly associated with sulphide minerals and the effective recovery of the sulphide minerals is therefore imperative (Cawthorn et al., 2002; Schouwstra et al., 2000). The majority of the PGMs are associated with pentlandite, either as inclusions within pentlandite grains or at the grain boundaries between pentlandite and gangue (Liddell et al., 1986). The bulk of Merensky ore consists of unwanted silicate gangue made up predominantly of pyroxene and plagioclase. Typically silicate minerals consist of a silicon atom surrounded by a tetrahedral group of four oxygen atoms (Fuerstenau, 1982). Talc is the only naturally floatable silicate mineral in Merensky ore, and may report to the concentrate thus lowering concentrate grade. Talc has a froth stabilising effect which is negated by the addition of depressant (Wiese 2009).

Polysaccharide depressants are normally added to reduce the recovery of the naturally floatable gangue minerals present in the ores. It has been shown that, using a high depressant dosage (500 g/t) all NFG can be depressed and the only gangue reporting to the concentrate is in the form of entrained gangue (Wiese, 2009). However, an increase in depressant concentration would lead to a decrease in froth stability because of the removal of a portion of the froth-stabilizing NFG. This in turn would lead to a decrease in the amount of entrained mass. It is also possible that if the adsorption of the collector on the sulfide minerals is weak or incomplete, the strongly hydrophilic depressant molecules could co-adsorb on the mineral surface and because of the

large size of these polysaccharide molecules, could interfere with particle bubble attachment, and reduce the subsequent recovery of the sulfide minerals (Wiese et al., 2008).

In order to counterbalance the negative effects of depressant addition, frothers are normally added. The optimum frother provides a balance between the pulp kinetics and the froth recovery (through the effect of the frother on the bubble size and froth stability, respectively) over the range of frother addition. Usually one frother is added to accomplish this but using only one frother gives only one unique hydrodynamic relationship. It would be preferable to have independent control over the bubble size and froth stability, but in most cases this cannot be achieved because changing the concentration of the frother changes both responses. An alternative strategy for gaining more independent control over the froth characteristics and bubble size would be to use a blend of frothers, such as a weak and a stronger frother. Such a system would give an additional degree of freedom so that changing the ratio of the two frothers would provide more independent control of bubble Sauter mean diameter and froth stability

2.4.3.3 Froth stability

Froth stability will normally affect both the flotation recovery and selectivity. Froth that is too stable will tend to entrain a significant amount of gangue material, which will consequently lead to a drop in concentrate grade. On the other hand froth with low stability will tend to break down and cause the packed material to drain out of the froth, increasing the grade but to the detriment of recovery.

Laboratory batch flotation tests have long been used to optimise reagent performance for application to large scale plants. The challenge has been establishing what measure can be used to assess froth stability. Since the particles entering the froth during flotation are changing continuously, it is difficult to measure such parameters as equilibrium froth height, froth drainage rates and dynamic froth index accurately during the limited time of collection (Wiese et al., 2011). However, it has been established that if the flotation cell is operated at a constant froth height, the water recovered in each concentrate can be used as an indication of the froth stability during the test and of the variation of froth stability during the test.

The measurement of the water recovered has another advantage in that the entrained mass is directly related to the water mass recovered and can therefore be used to decouple the gangue

reporting to the concentrate by entrainment from that recovered by true flotation (Wiese et al., 2011). This has resulted in the development of a methodology to quantify the effects of reagents on froth stability as part of the understanding and assessment of the performance of reagents in flotation. The same method will be used in this study as the measure of froth stability, and will be described in section 2.4.3.4.

2.4.3.4 Entrainment

Entrainment of unwanted material into the froth is an important factor to consider when analyzing the performance of a flotation cell. Entrainment has been defined as the non-selective recovery of both valuable minerals and gangue materials, carried upwards by the rising air bubbles and water to the froth (Neethling and Cilliers, 2002). This unselective recovery of materials to the froth in turn lowers the concentrate grade. Entrainment is dependent on the froth stability and mobility (which depends largely on the air flowrate). The relationship between gangue recovered and fractional water recovered is normally referred to as the entrainment factor or degree of entrainment. It is defined as the recovery of entrained species divided by recovery of water (Zheng et al., 2006).

There are several methods that can be used to quantify the amount of entrained materials in batch flotation tests. A method developed at the University of Cape Town (UCT) and used in this investigation makes use of the entrainment function calculated from flotation experiments carried out at high dosage of depressants (Wiese, 2009). The method, developed for use in the analysis of PGM flotation experiments, assumes that at high depressant dosage all floatable gangue has been depressed and the only gangue reporting to the concentrate will be due to entrainment. Figure 2.9 shows the test conducted using this method to determine the amount of total gangue recovered as a function of water recovered (Wiese and Harris, 2012). The test was conducted on the ores from the southern section of the Merensky reef in the Bushveld Igneous Complex, South Africa. The frothers, Dow 200 and Dow 250 were used at dosages of 40, 50 and 60 g/t. The collector, sodium isobutyl xanthate (SIBX) was used at a dosage of 150 g/t and the polymeric depressants Depramin 267, a carboxymethylcellulose and Stypres 504 were used at dosages 500 g/t. The gradient of the line is equivalent to the entrainment factor and is equal to the amount of entrained material reporting to the concentrate per unit water recovered. This entrainment factor for the particular ore, grind and pulp density can then be used at lower

depressant dosages to determine the amount of naturally floatable gangue reporting to the concentrate by flotation. Total gangue is calculated by removing sulphide mass from the total mass of each concentrate. Entrained gangue is then subtracted from total gangue to determine floating gangue (Wiese, 2009).

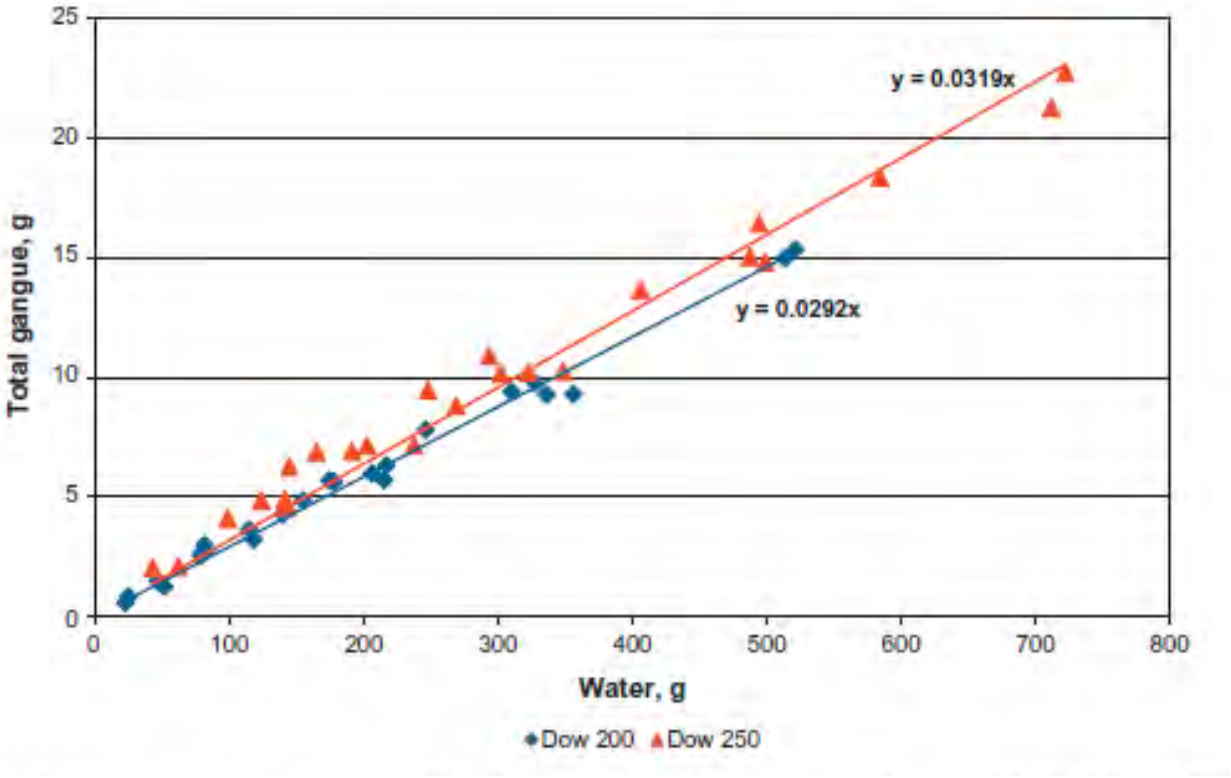

Figure 2.9 Total gangue versus water recovered for tests conducted at various dosages of DOW 200 and DOW 250 (Merensky ore, Frothers: Dow 200 and Dow 250 at dosages of 40, 50 and 60 g/t, Collector: SIBX, 150 g/t, Depressant: Stypres 504, 500 g/t) (Wiese and Harris, 2012)

2.5 Frother Blends

The reviewed literature suggests that it is difficult to obtain independent control over bubble size and froth stability using a single frother. Frothers that are known to be stronger tend to be effective in recovering coarse particles, but with poor selectivity; frothers that are considered weak tend to be very selective, but float coarse particles with difficulty. It has also been observed that weak frothers like pentanol are very effective in bubble size reduction but the bubbles

generated rise with little retardation, whereas stronger frothers like F150 cannot produce such small bubbles but introduce significant retardation.

It is therefore considered that a blend of strong frother and a weak frother will be able to produce a frother mixture that can have improved recovery of particles over a wide range of size fractions, but with better selectivity and less persistence. There are currently very few reported studies that have been conducted on frother blends and the discussion of these follows after a brief review of micelles.

2.5.1 Micelle Formation and Properties

In order to properly understand the behaviour of frother blends in flotation, it is important to first introduce the concept of micelles. A micelle is an aggregate of frother molecules dispersed in an aqueous solution, usually formed when a variety of molecules are present in the water. The molecules must have a strongly polar head and a non-polar hydrocarbon chain tail. Micelles only form when the concentration of a frother is higher than its critical micelle concentration (CMC). Figure 2.10 shows the formation of micelle as frother concentration is increased. Molecular orientations serve to reduce the total free energy of the solution through the formation of molecular aggregates with their hydrophobic portions directed toward the interior of the micelle. Micellization, therefore, is an alternative mechanism to adsorption for the reduction of solution free energy by the minimization of the distortion of the structure of the bulk water (Myers, 2006).

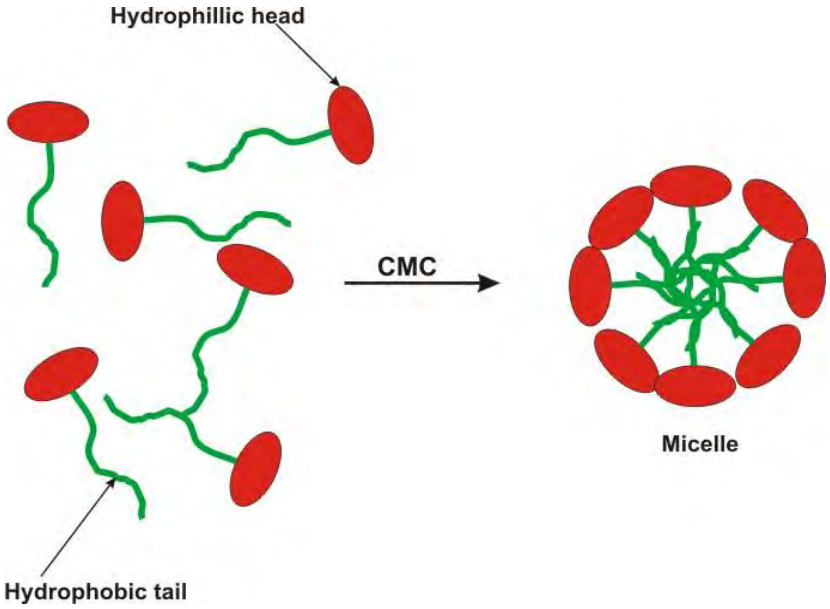

Figure 2.10 Micelle formation with increasing frother concentration

The properties of a surfactant solution normally change much more rapidly with the introduction of small amounts of long-chain alcohols, especially C4 and higher. Lower alcohols would not be expected to partition into the interior of the micelle when present in small amount. The short chain alcohols have been known with their tendency to remain in solution thereby promoting the formation of expanded water structures around hydrophobic region of the alcohols molecules (Mukherjee et.al, 2011) which may result in increased surface tension of the system. The presence of such short chained alcohols which are infinitely miscible in water will modify the solvent water leading to the formation of less polar medium which cause a restriction to the micellization (Li et.al, 2009). For long chain alcohols, the inherent surface activity can become significant.

Aliphatic alcohols having four or more carbon atoms penetrate the polyglycol micelles forming a mixed micelle. This adsorbs at the air–water interface and competes for position in the surface layer with the polyglycol molecules (Samanta and Ghosh 2011).

In frothers with a range of molecular weights, as in the case of alcohols and polyglycols, the smaller chains will routinely adsorb first, but they also desorb more readily and are, over time, replaced by the higher-molecular-weight chains (Myers, 2006).

Each mixed micelle contains several hydrophobes either from a chain or from different chains. At low frother concentrations, nearly all frother molecules are associated with the polyglycol in the formation of mixed micelles. At high frother concentration, such binding reaches a saturation point, beyond which free micelles are expected to coexist with the mixed micelles (Mukherjee et.al, 2011). At higher frother concentrations, the free micelles greatly outnumber the mixed micelles, almost approaching the value of the pure surfactant solution at the same concentration.

Frother blends investigated in this work can be expected to follow the principles of micelles. Formation of alcohol-polyglycol mixed micelles can be expected when using the blends.

2.5.2 Effects of frother blends

In a study to investigate the effect of blending frothers, Tan et al. (2005) conducted experiments to test the froth properties of polypropylene glycol surfactant blended with MIBC (Figure 2.11). They found a synergistic effect with the mixed system: the froth height in the presence of the blend was larger than the summation of the froth heights formed by each frother alone. The mixtures were also found to have a much greater effect on surface tension reduction compared to the pure frothers. In another study Laskowski et al (2003) tested the frothing properties of blends of MIBC with a series of polyoxypropylene alkyl ethers, through measuring their effect on the bubble size and the dynamic foamability index. Figure 2.12 shows the effect of a blend of MIBC and DF-1012 on bubble size measured in an open top Leeds flotation cell. They observed that the small addition of a more powerful polyglycol frother to MIBC dominated the properties of the mixture.

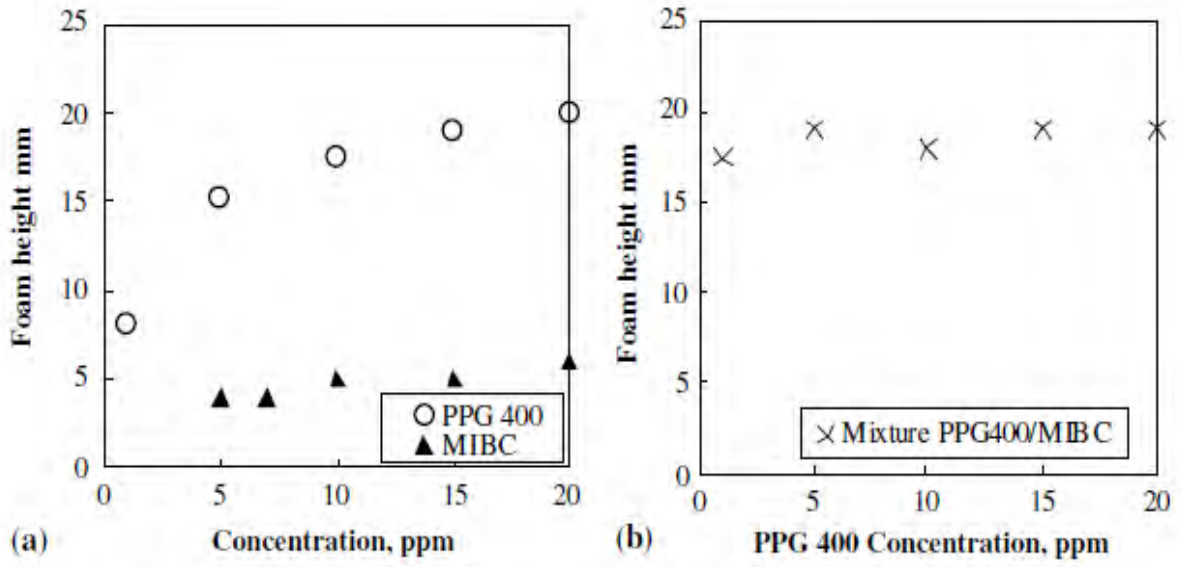

Figure 2.11 Foam behaviour of (a) PPG400 and MIBC from 0 to 20 ppm and (b) PPG400/MIBC mixture at a total concentration of 20 ppm (Tan et al., 2005)

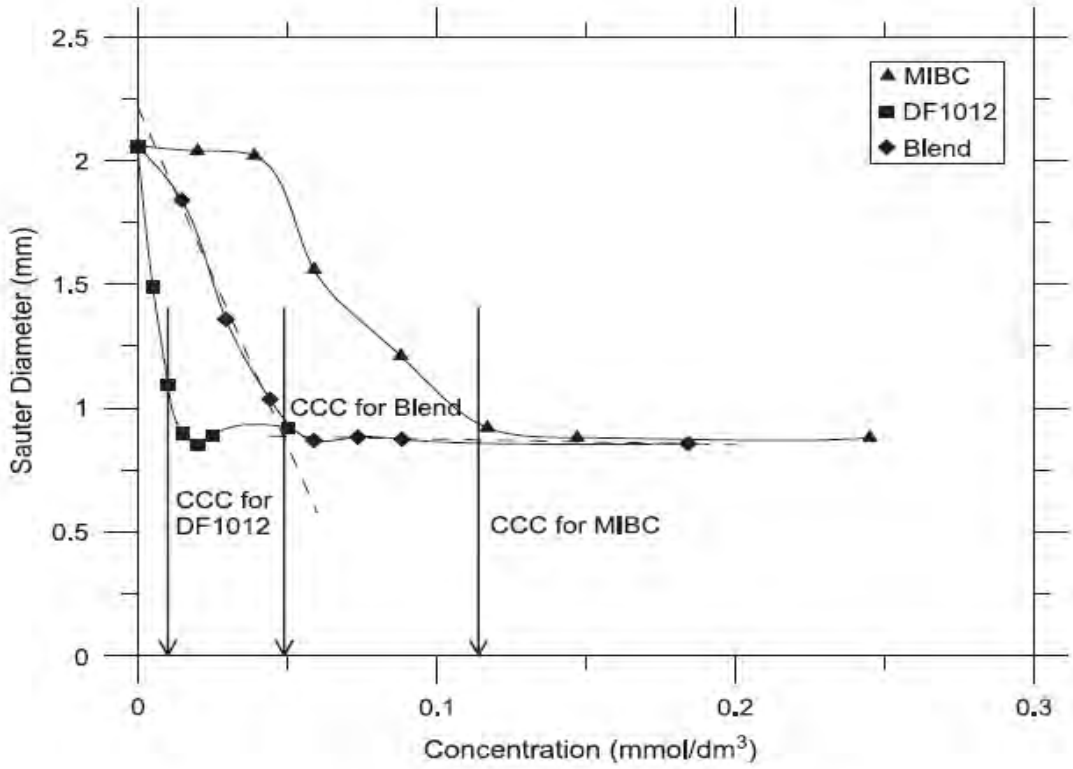

Figure 2.12 Effect of MIBC and DF-1012 blend on bubble size (Laskowski et al., 2003)

Elmahdy and Finch (2009) studied the effect of blends of F150 (polyglycol) with MIBC or pentanol (alcohol) on bubble size, gas hold up and froth height measured using a 3.5 m x 10 cm

diameter Plexiglas bubble column. They observed that at concentrations below the alcohol CCC, the bubble size was reduced significantly compared to either polyglycol or alcohol alone. In contrast, the bubble size above the alcohol CCC was significantly larger than for alcohol alone. They argued that bubble size above CCC was not the original bubble size produced by the bubble generation mechanism and that prevention of coalescence is not the only mechanism controlling bubble size production. They suggested that the larger bubble size obtained above the alcohol CCC might be due to reduced breakage or increased coalescence events.

In an attempt to understand the impact of frother blends on metallurgical performance, Hernandez-Aguilar et al. (2006), in a plant study at the Lac des Iles palladium (Pd) operation, investigated the poor recoveries of very fine (less than 10 μm) Pd compared to what was projected from initial pilot plant studies by Martin et al. (2003). An investigation in 2003 postulated that insufficient small bubbles in the plant cells was the main cause of the poor recoveries, as the plant operated with MIBC as a frother below the CCC (Nesset et al., 2005). In a follow-up study in 2005, a blended alcohol-polyglycol frother was added to the same cells in an attempt to reduce Sauter mean diameter, again measuring gas dispersion parameters and metallurgical behaviour (Hernandez-Aguilar et al. 2006).

Figure 2.13 shows the gas dispersion data from the 2003 and 2005 studies, showing that the plant was operating under the same hydrodynamic conditions during both studies. The 2003 pilot plant data shows significantly smaller D_{32} (upper plot) and higher Sb (lower plot) values. Addition of a stronger blended frother achieved the desired results of having the D_{32} and Sb values match the pilot plant study data. As a result, the recovery of -10 μm Pd increased from below 20% to over 60%. This shows the impact that frother blends can have on the metallurgical performance of a circuit.

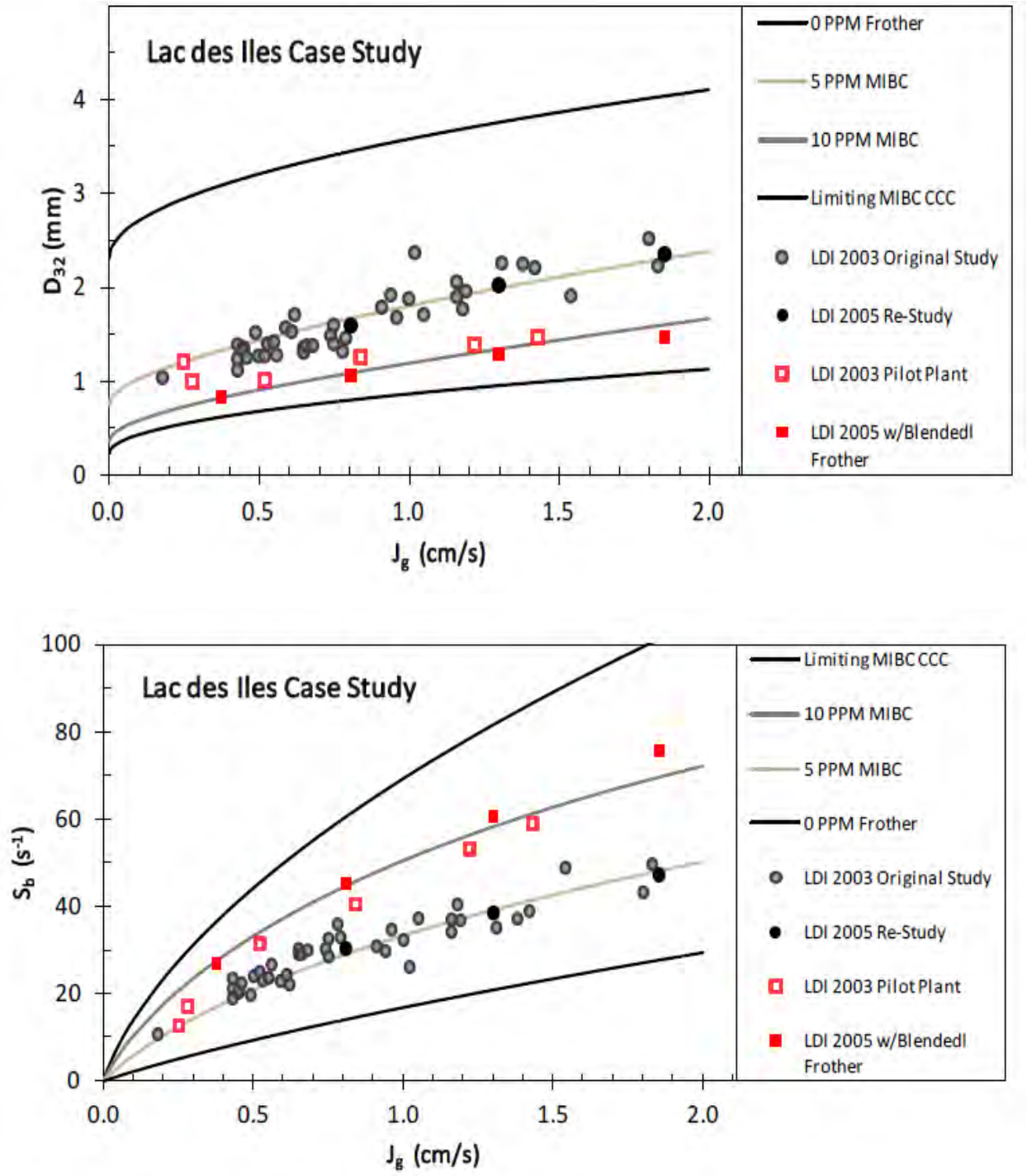

Figure 2.13 The Lac des Iles case study gas dispersion roadmaps. Circles indicate 2003 and 2005 plant data. Squares indicate the 2003 pilot plant data which was matched in 2005 by the use of a stronger, blended frother than MIBC (Nesset et al., 2012)

A recent study was carried out by Zhang et al. (2012a) to characterize dual alcohol/polyglycol frother systems by measuring the bubble size, gas holdup and water overflow rate in a two phase

system, with the objective of determining blends that achieve independent control over hydrodynamic and froth properties. Their results (Figure 2.14) show that it is possible for a frother blend to allow independent control over the froth properties, i.e. water overflow rate, which is the measure of stability, and the two pulp hydrodynamic properties, Sauter mean bubble diameter and gas hold up. It can be seen from the results with the 1-butanol/tetraethylene glycol blend that gas hold up and water flowrate increased upon addition of tetraethylene glycol concentration but the Sauter mean diameter was independent of the additive.

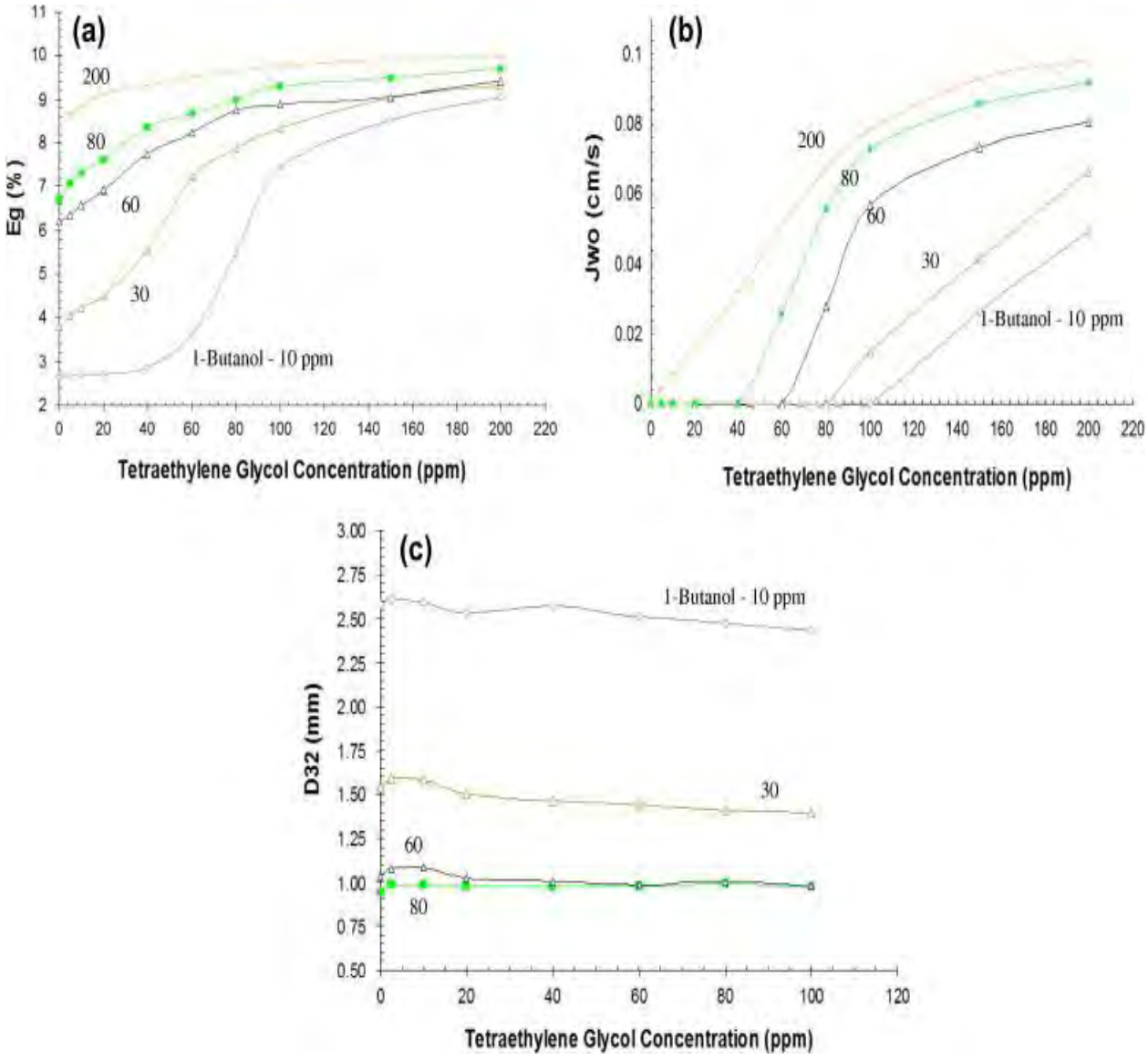

Figure 2.14 Effect of tetraethylene glycol (additive) concentration on (a) gas holdup – Eg; (b) water overflow rate – Jwo; and (c) bubble size – D32, in the presence of 1-Butanol (base) at various concentrations (Zhang et al, 2012a)

Gupta et al. (2009) conducted a research program to compare the effects of various frother mixtures on the froth flotation performance for a widely size distributed coal flotation feed. In this experiment three mixed frother systems were prepared: frother "x" composed of alcohol and ketone; frother "y" composed of alcohol and aldehyde group chemicals; and frother "z", composed of alcohol and polyglycol ether. Figure 2.15 and Figure 2.16 show that the alcohol and polyglycol ether mixture frother "z" was clearly superior compared to the other mixtures in terms of selectivity and kinetics. It was also efficient for both coarse and ultrafine particle size fractions and more surface active in reducing the surface tension compared to other two frothers (as can be seen in Figure 2.17).

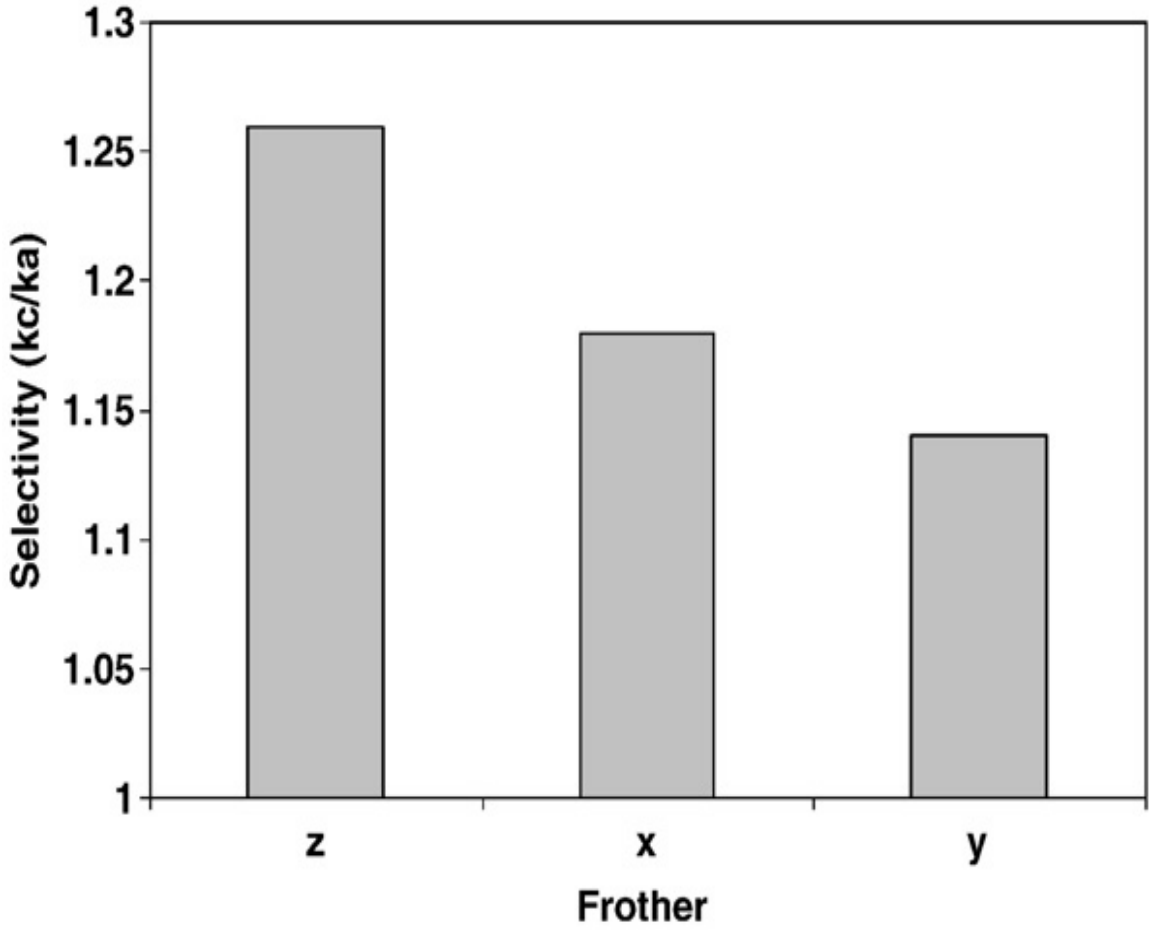

Figure 2.15 Selectivity in coal flotation for three mixed chemical systems at optimum operating conditions (0.175 kg/t collector, 11 ppm frother, 2 lpm air flow rate, 10% solid content in feed and 850 rpm impeller speed) (Gupta et al., 2009).

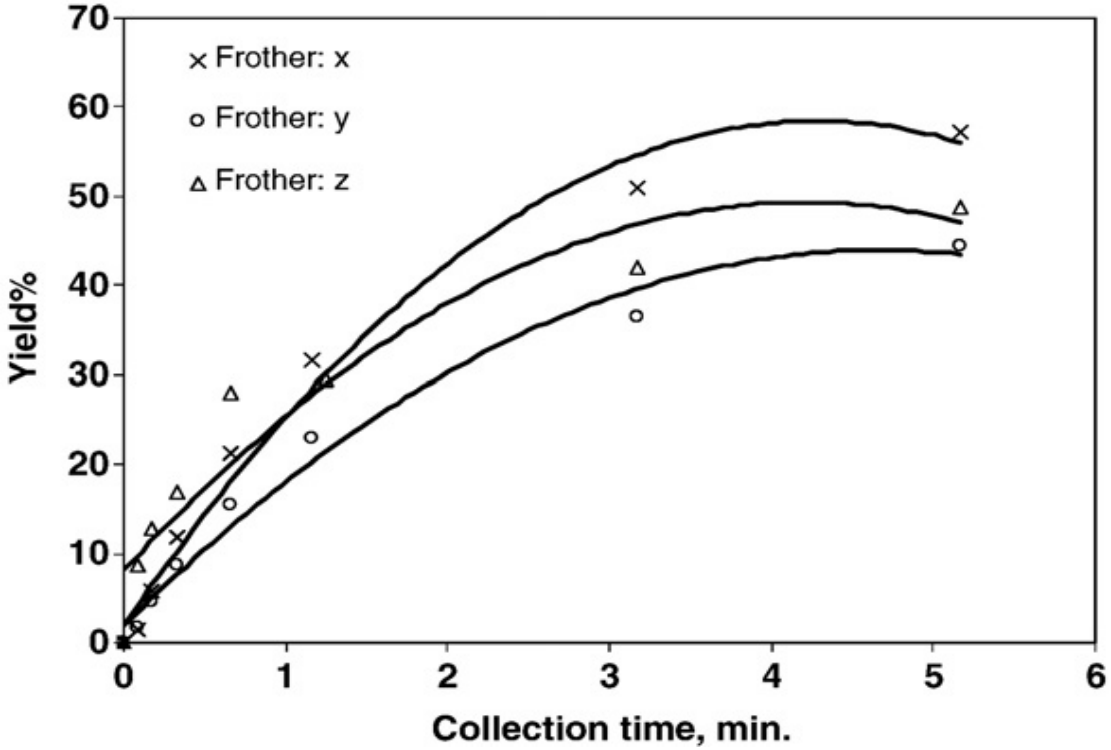

Figure 2.16 Comparison of mixed frothers on the basis of kinetics (yield–time relationship).at optimum operating conditions (0.175 kg/t collector, 11 ppm frother, 2 lpm air flow rate, 10% solid content in feed and 850 rpm impeller speed) (Gupta et al., 2009).

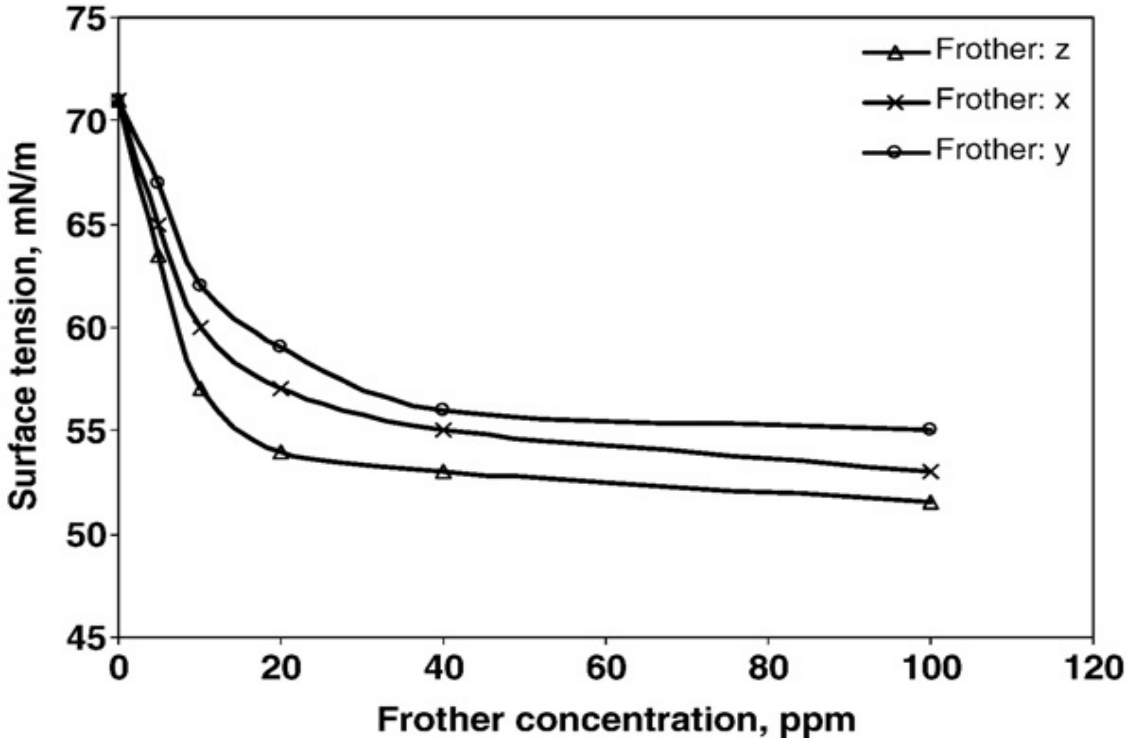

Figure 2.17 Equilibrium surface tension vs. frother concentration for frothers ‘x’, ‘y’ and ‘z’ (Gupta et al., 2009).

2.6 Summary of literature review

The selection of chemical reagents to be used in froth flotation processes is of critical importance. Reagents manipulate the surface properties of particles and create stable bubbles. Many different reagents are involved in the flotation, with the selection of reagents depending on the specific ore type being treated.

Frothers are an important group of reagents used in the flotation of platinum bearing minerals. Frothers are heteropolar surface active compounds containing a polar group and a hydrocarbon radical, which are capable of adsorbing at the air-water interface and creating conditions for froth formation. Frother molecules effectively form an envelope around the bubbles, which prevents them from colliding or touching. Frothers also lower the surface tension of the water. Many frother types exist, of which the most common can be classified as alcohols, alkoxy-type frothers or polyglycol-type frothers.

The polyglycols are the strongest surface active frothers utilised. The most common group of polyglycols includes the polypropylene glycol methyl ethers represented by the formula $CH_3 – (O – C_3H_6)n – OH$ and the polypropylene glycols represented by the formula $H-(O-C_3H_6)n-OH$. They are completely miscible in water, and produce compact, lasting froth structures that break down readily in the launders. The polyglycols produce more stable and viscous froths compared to alcohol frothers, which enables the recovery of coarse particles in the flotation feed.

Aliphatic alcohols are mixtures of alcohols containing 5–8 carbon atoms. The best known alcohol frothers are methyl isobutyl carbinol (MIBC) and 2-ethyl hexanol. Aliphatic alcohol frothers are used as mixtures of different carbon lengths. Aliphatic alcohol frothers are known to show less tenacity, lower water retention and produce more brittle froths than the polyglycols. They have relatively low water solubility and are highly selective in the flotation of fine to medium particle sizes when used at low to moderate dosage at higher pH. For most of the aliphatic alcohols frothers, increasing the frother dosage can improve the recovery of large particles. However the economics become less desirable and there are usually selectivity problems in the circuit with the consequence that the overall rate of recovery consequently starts to drop. This indicates that there is always a practical operable range for a given frother in a flotation circuit beyond which undesirable events start to occur.

Froth stability will normally affect both the flotation recovery and selectivity. Froth that is too stable will tend to entrain a significant amount of gangue material, which will consequently lead to a drop in concentrate grade. On the other hand, froth with low stability will tend to break down and cause the packed material to drain out of the froth, increasing the grade but to the detriment of recovery. Froth stability is therefore a key parameter that influences flotation performance. In the three phase system, froth stability is generally controlled by the attached solids and the chemistry of the solution.

Polysaccharide depressants are normally added in PGM concentrators to reduce the recovery of the naturally floatable gangue minerals (mainly silicates) present in the ores. High depressant dosage can depress all NFG but this would lead to a decrease in froth stability because of the removal of a portion of the froth-stabilizing NFG, which in turn would lead to a decrease in recovery of the sulfide minerals. In order to offset the negative effects of depressant addition, frothers are normally added. It would be preferable to have independent control over the bubble size and froth stability, but unfortunately this cannot be achieved with one frother because changing the concentration of the frother changes both responses. An alternative strategy would be to use a blend of frothers, such as a weak and a stronger frother.

There are currently very few reported studies that have been conducted on frother blends (Laskowski et al 2003; Tan et al. 2005; Hernandez-Aguilar et al. 2006; Elmahdy and Finch 2009; and Zhang et al 2012a,b). Synergistic effects with the mixed system have been reported in some studies with froth height in the presence of the blend being larger than the summation of the froth heights formed by each frother alone. Mixtures have also been found to have much larger effect on surface tension reduction compared to the pure frothers. In a plant study investigating the poor recoveries of very fine Pd, it was observed that addition of a stronger blended frother achieved the desired results with the recovery of -10 μm Pd increasing from below 20% to over 60%. Most recently, a study to characterized dual alcohol/polyglycol frother systems by measuring bubble size, gas holdup and water overflow rate with the objective of determining blends that achieve independent control over hydrodynamic and froth properties was conducted and concluded that it is possible for the frother blend to have independent control over the froth properties. In a research program to compare the effects of various frother mixtures on the froth flotation performance for a widely size distributed coal flotation feed, it was found that a frother

mixture composed of alcohol and polyglycol ether was clearly superior compared to the other mixtures in terms of selectivity and kinetics. It was also efficient for course and ultrafine particle size fractions and more surface active in reducing the surface tension compared to other frothers.

A laboratory method for assessing froth stability has been developed at UCT based on the water recovered in each concentrate. The measurement has another advantage in that the entrained mass is directly related to the water mass recovered and can therefore be used to decouple the gangue reporting to the concentrate by entrainment from that recovered by true flotation. This method can be used to investigate the effects of reagents on froth stability.

The reviewed literature suggests that it is difficult to obtain independent control over bubble size and froth stability using a single frother. Frothers that are known to be stronger tend to be effective in recovering course particles but with poor selectivity; frothers that are considered weak tend to be very selective but float course particles with difficulty. It has also been observed that weak frothers like pentanol are very effective in bubble size reduction but the bubble generated rise with little retardation, whereas stronger frothers could not produce such small bubbles but introduced significant retardation. It is therefore considered that a blend of strong and a weak frother will be able to produce a frother mixture that can have improved recovery of particles over a wide range of size fractions but with better selectivity and less persistence.

This study therefore concentrates on blending polyglycol and alcohol frothers in order to improve the flotation of platinum bearing minerals in Merensky ore. It measures their effect on solids and water recovery, bubble size reduction and bubble size distribution.

CHAPTER THREE
EXPERIMENTAL DETAILS

3.1 Introduction

The main objective of this research was to investigate the behaviour of frother blends in the flotation of platinum bearing Merensky reef ores. It has been hypothesised that blending of low molecular weight alcohol and polyglycol frothers will enhance the individual ability of these compounds to reduce bubble size and increase froth stability, thereby improving valuable mineral recovery. In order to test this hypothesis, a series of batch flotation tests was performed to compare the recoveries of valuable minerals from two Merensky reef ores using low molecular weight alcohol and polyglycol frothers individually or in blends. Experiments to determine entrainment for both ores were also performed. Finally bubble size measurements were made for both single frothers and frother blends. This chapter describes the materials and experimental procedures used in the study. It includes a description of the major items of equipment used, the ores and reagents tested and the analytical methods employed.

3.2 Equipment used

3.2.1 Flotation cell

A modified Leeds flotation machine, manufactured by Chamic Engineering, and consisting of a perspex flotation cell with a capacity of 3 L and a top driven impeller, was used to conduct all the batch flotation tests. The cell was fitted with a variable speed drive. The airflow through the cell was supplied by a compressor and was controlled by the use of a 6 mm diameter, 0-8 bar air regulator. The pulp level was controlled manually by the addition of synthetic plant water. Figure 3.1 shows a photograph of the flotation cell used in the study.

3.2.2 Jaw and cone crushers

One of the samples (#2) was received as a blend of 1 mm to 200 mm material. A jaw crusher manufactured by Sturtevant was used to reduce the size of larger rocks to pebbles with diameters of approximately 15 mm. A cone crusher manufactured by Osborn MMD was then used to crush the sample to 100% passing 3 mm. The crushed sample was blended, riffled and split into

representative 1 kg sub-samples using a rotary sample splitter manufactured by Dickie and Stockler.

3.2.3 Mill

A laboratory scale Eriez stainless steel rod mill with a diameter of 200 mm was used for grinding the ores to the particle size required for flotation. The mill was charged with a set of twenty stainless steel rods made up as follows: 6 x 25 mm diameter, 8 x 20 mm diameter and 6 x 16 mm diameter.

Figure 3.1 Flotation cell used in the study

3.2.4 Bubble sizer

The UCT bubble sizer was used to measure the bubble sizes formed in the presence of different frothers and frother blends.

Figure 3.2 shows the schematic diagram of the UCT bubble size analyser. It consists of a glass capillary placed inside a glass column filled with the solution of interest, a detector head which contains two optical detectors mounted at right angles to each other, detector electronics, a microprocessor, a computer, a peristaltic pump and a gas burette. Bubbles are suctioned through a capillary tube and collected in a gas burette. As a single bubble travels up the capillary, two optical sensors produce signals that are used to produce two pulses for each bubble. These pulses are used to calculate the velocity and the volume of the bubble. The total volume collected in the gas burette during the measurement is used to calculate the absolute size of the bubbles. A detailed description of the instrument has been published by Randall et al. (1989).

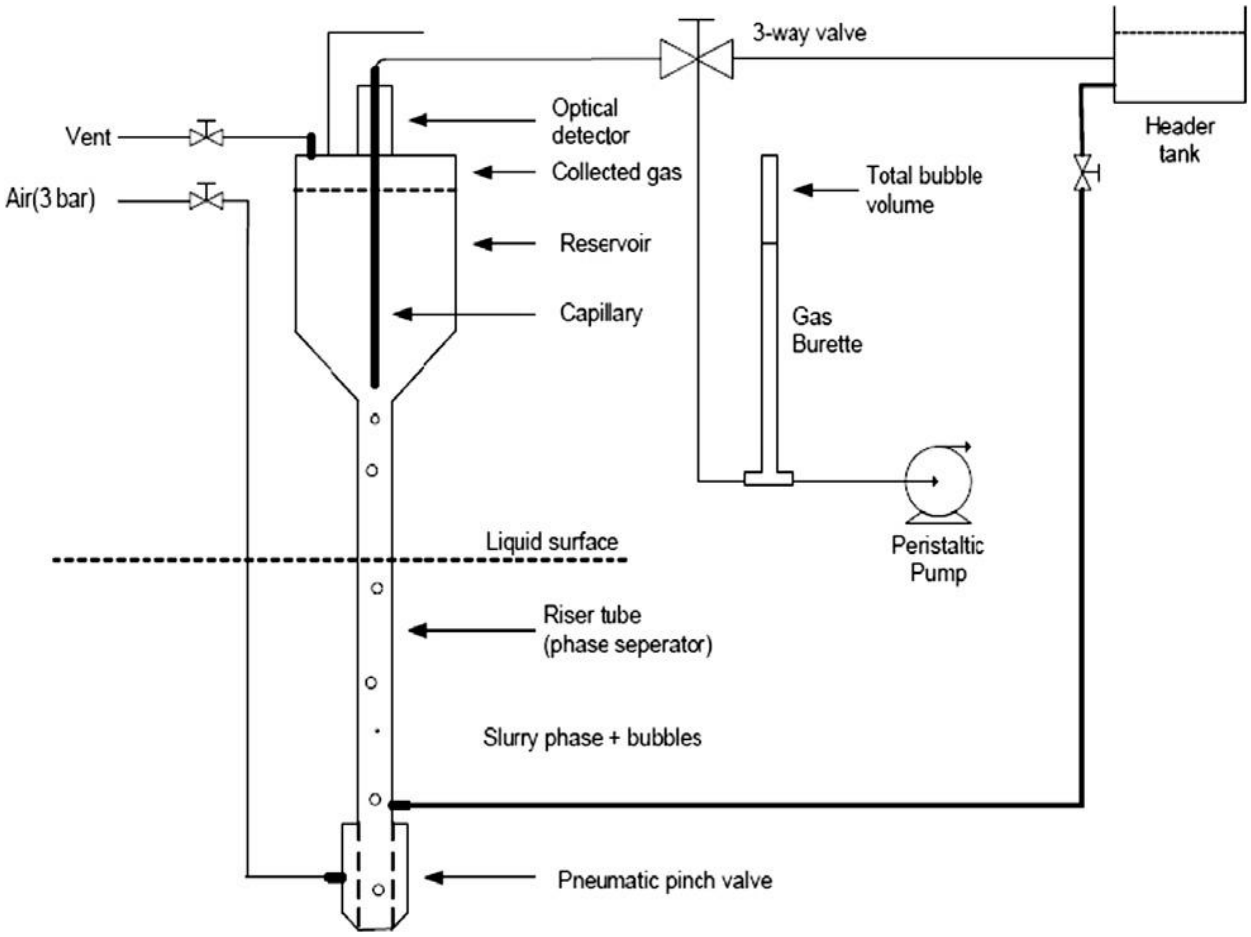

Figure 3.2 Schematic diagram of UCT bubble size analyser (Randall et al. 1989; Randall, 2009)

3.3 Materials used

3.3.1 Feed Samples

Samples of two ores from the Merensky reef in the Bushveld Complex, South Africa, were used in the study. In this thesis the ores will be referred to as ore # 1 (Turfontein Merensky) and ore # 2 (Impala Merensky). Ore # 1 was received as 1 kg pre-packaged sub 3 mm crushed samples. Ore # 2 was received as a blend of 1 mm to 200 mm material and was prepared at the CMR, UCT, as described in section 3.2.2. The mean copper, nickel and sulphur grades of the two ore samples are shown in Table 3.1. These are the averages of the reconstituted feed grades calculated using the concentrate and tailings values obtained from all the batch flotation tests.

Table 3.1 Mean calculated feed values for the two ores used in this study

Ore Sample	Copper, wt %	Nickel, wt %	Sulphur, wt %
#1	0.074	0.178	0.322
#2	0.056	0.143	0.238

3.3.2 Flotation reagents

Sodium isobutyl xanthate (SIBX) was used as a collector for all the batch flotation tests. Stypres 504, a modified guar gum with a molecular weight of about 230 000 g/mol, was used as a depressant. Polyglycol frother types used in the study were Senfroth 516, DOW 200 and DOW 250. Table 3.2 shows the properties of polyglycol frothers used in the study.

Table 3.2 Properties of Polyglycols used in the study (Khoshdast and Sam, 2011)

Polyglycols	Formula	Molecular weight (g/mol)	Solubility
DF 200	$CH_3(C_3H_6O)_3OH$	206.29	Total
DF 250	$CH_3(C_3H_6O)_4OH$	264.37	Total
SF 516	Blend of PPG frothers	220.00	Total

Alcohol frother types used in the study were 1-butanol, 1-pentanol, 1-hexanol and MIBC. Table 3.3 shows the properties of the alcohols used.

Table 3.3 Properties of aliphatic alcohols used in the study (Khoshdast and Sam, 2011)

Alcohols	Formula	Molecular weight (g/mol)	Solubility (g/l)
[1]1-Butanol	$CH_3(CH_2)_3OH$	74.12	77
1-Pentanol	$CH_3(CH_2)_4OH$	88.15	27
1-Hexanol	$CH_3(CH_2)_5OH$	102.17	5.9
MIBC	$(CH_3)_2CHCH_2CHOHCH_3$	102.17	17

The collector, SIBX, was supplied by Senmin in powder form at close to 100% purity. The collector was made up fresh each day as a 1% solution using distilled water. The depressant, Stypres 504, was supplied by Chemquest in powder form. It was made up as a 1% solution by hydrating the powder in distilled water for 2 hours using a magnetic stirrer to avoid the formation of lumps.

Senfroth 516 frother was supplied by Senmin in concentrated form. Dow 200 and Dow 250 were supplied by Betachem, also in concentrated form. The alcohol frothers were supplied by Sigma Aldrich. All frothers were dosed as is. The frothers were used individually and as blends at a total dosage of 50 g/t. The frother blends investigated in the study are shown in Table 3.4.

Table 3.4 Frother blends investigated in this study

Frother	**Dosage, g/t**					
1-pentanol	50	40	30	20	10	0
Senfroth 516	0	10	20	30	40	50
Dowfroth 200	50	10	40	0		
1-pentanol	0	40	10	50		
Dowfroth 200	50	10	40	0		
1-hexanol	0	40	10	50		
Dowfroth 200	50	10	40	0		
MIBC	0	40	10	50		
Dowfroth 250	50	10	40	0		
1-pentanol	0	40	10	50		
Dowfroth 250	50	10	40	0		
1-hexanol	0	40	10	50		
Dowfroth 250	50	10	40	0		
MIBC	0	40	10	50		

[1] 1-butanol was also used, but produced no froth at all and was omitted from the results

Copper and total nickel analyses of all samples were done using a Bruker S4 Explorer XRF spectrophotometer. Sulphur analysis was carried out using a LECO S 632 sulphur analyser. The results obtained for chemical assays were used to calculate the grades and recoveries of the available minerals. PGM assays were not performed due to time and financial constraints, but previous work using Merensky ores showed that copper and nickel recoveries followed the PGMs and so prove to be good proxies for PGMs.

3.3.3 Water

Synthetic plant water was used in all the experiments. Various chemical salts, supplied by Merck, were added to distilled water to obtain total dissolved solids of 1023 ppm in order to simulate conditions found on concentrators processing PGM ores (Wiese et al., 2009). Table 3.5 shows the ionic concentration of all ions present in the synthetic plant water used in the study.

Table 3.5 Ionic concentrations of all ions present in the synthetic plant water used in the study (Wiese, 2009)

Ion	**Ca^{2+}**	**Mg^{2+}**	**Na^{+}**	**Cl^{-}**	**SO_4^{2-}**	**NO_3^{-}**	**CO_3^{2-}**	**TDS**
Concentration (ppm)	**80**	**70**	**153**	**287**	**240**	**176**	**17**	**1023**

3.4 Experimental procedure

3.4.1 Comminution for ore # 2

The sub 3 mm samples of ores #1 and #2 were milled prior to flotation. 1 kg portions of the ore samples were milled at 66% solids in synthetic plant water to achieve a grind of 60% passing 75 μm. A solution of 1% sodium isobutyl xanthate (SIBX) collector at a constant dosage of 150 g/t was added to the mill prior to grinding. The two ores used in the study required different milling times in order to achieve the required grind. Figure 3.2 shows the milling curves for the ores used in the study.

3.4.2 Flotation

The batch flotation procedure developed at the Centre for Minerals Research, University of Cape Town (Wiese et al., 2005), was used throughout this work. The milled slurry was transferred to the flotation cell and made up to 35% solids using synthetic plant water. The impeller was turned

on and set at 1200 rpm. The depressant was added at a dosage of 250 g/t for all batch flotation tests and allowed to condition for two minutes. Frother was added last and allowed to condition for one minute. Air was turned on and set at a flow rate of 7 L/min. Four concentrates were collected at 2, 6, 12 and 20 min of flotation time by scraping the froth into a collecting pan every 15 s. A feed sample was taken before and a tailings sample was taken after each test. Feeds, concentrates and tails were filtered, dried, weighed and analysed for copper, nickel and sulphur. Water recoveries were measured for each test concentrate. All tests were conducted in duplicate. Error bars displayed on figures indicate the standard deviation between duplicate tests.

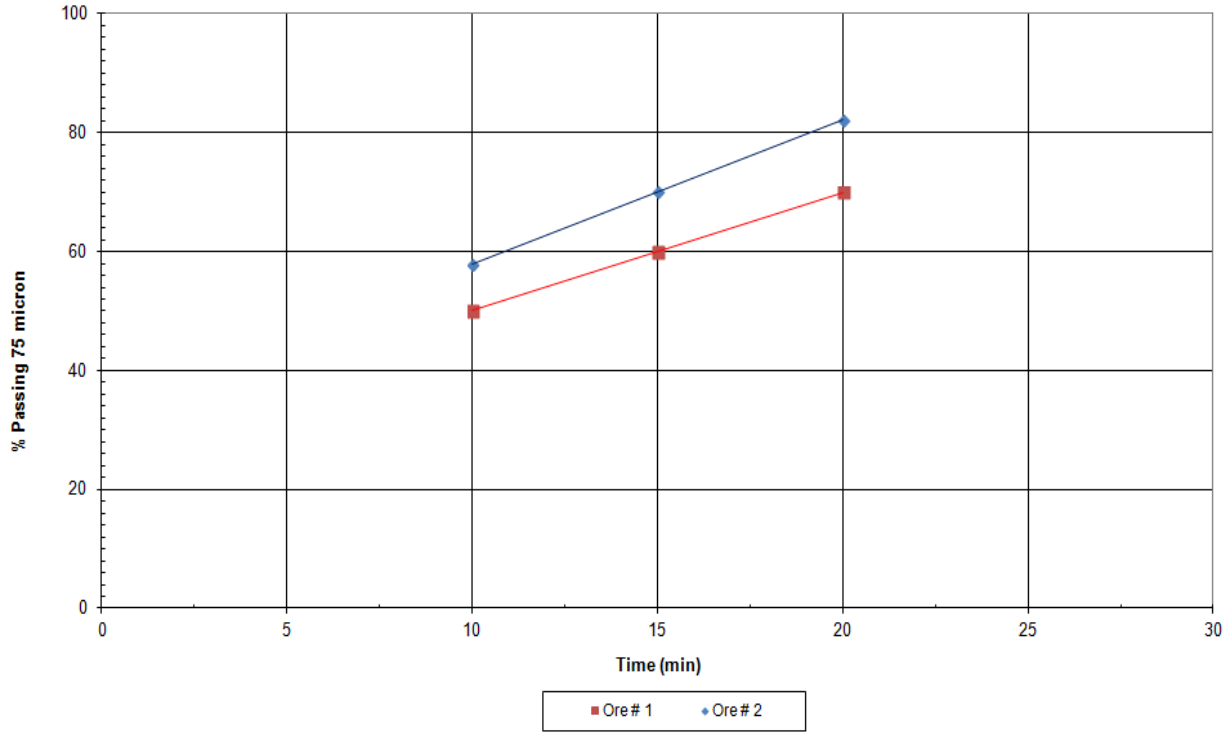

Figure 3.2 Milling curves for the ores used in the study

3.5 Determination of entrainment

A series of tests was conducted in order to quantify entrainment of material in both ores used in this investigation. The method developed at UCT (Bradshaw et al., 2005) was used, in which it is assumed that at high depressant dosages, all naturally floatable gangue has been depressed and that the gangue reporting to the concentrate under these conditions will be present due to entrainment only. The entrainment factor is obtained as the gradient of the total gangue reporting

to the concentrate plotted against water recovered. (The gangue recovery to the concentrate is calculated by subtracting the sulphide mass recoveries from the total solids recovery). The entrainment factor is then used at lower depressant dosages to determine the amount of naturally floatable gangue reporting to the concentrate by flotation.

Batch flotation tests to determine entrainment were performed with both ores. Guar gum, Stypres 504, was used as depressant at dosage of 500 g/t and the collector used was the same as in the initial test work. Frother type and dosage were selected from the tests that produced optimum results in the first set of experiments. Dow 200 was used first on its own at a dosage of 50 g/t and was then blended with MIBC at a ratio of 4:1 yielding a total dosage of 50 g/t.

3.6 Bubble size measurements

Bubble size measurements were performed using dilute solutions of alcohol and polyglycol frothers in their pure form as well as blends. The three alcohol type frothers and the two polyglycol type were used in this series of experiments. The polyglycol frothers were used as base at a constant dosage of 2 ppm with alcohol being added incrementally. Table 3.6 shows frother types and dosages used in this batch of experiments. Three or more runs were carried out for each of the frother concentrations and blends tested, using the UCT bubble sizer (Tucker et al. 1994).

Table 3.6 Frother type and dosage used in bubble size measurements in ppm

MIBC	Dow 200
3	2
8	2
13	2
18	2
23	2
28	2

MIBC	Dow 250
3	2
8	2
13	2
18	2
23	2
28	2

1-hexanol	Dow 200
3	2
8	2
13	2
18	2
23	2
28	2

1-pentanol	Dow 200
3	2
8	2
13	2
18	2
23	2
28	2

1-pentanol	Dow 250
3	2
8	2
13	2
18	2
23	2
28	2

1-hexanol	Dow 250
3	2
8	2
13	2
18	2
23	2
28	2

CHAPTER FOUR

RESULTS

4.1 Introduction

Experiments were conducted to investigate the effect of frother blends in the flotation of two PGM bearing ores selected from the Merensky Reef in the Bushveld Igneous Complex, South Africa. The experiments involved the use of batch flotation tests, using frothers selected to cover a range of polyglycols and alcohols. Preliminary work was carried out to establish the frother blend ratios to use in the main flotation testwork. Flotation experiments were also carried out at high depressant dosage to determine how much of the additional solids recovery could be attributed to entrainment. Two phase tests were then carried out to measure the bubble size distributions formed in the presence of various combinations of frothers.

This chapter presents the results of all the experiments. It begins with the preliminary work and proceeds to the main flotation experiments. It also includes the results of entrainment tests and the bubble size measurements. All flotation tests were conducted in duplicate; the graphs show the average values, with the bars indicating standard deviations. The raw data can be found in the appendices.

4.2 Preliminary work

The preliminary experiments were carried out to establish the frother blending ratios that would yield better results than using individual frothers on their own. Senfroth 516 and 1-pentanol were selected to represent polyglycol and alcohol frothers, respectively. Figure 4.1 shows the final solids and water recoveries (by mass) from flotation tests conducted on Merensky ore #1 using Senfroth 516 and 1-pentanol individually, and as blends in ratios of 1:4, 2:3, 3:2 and 4:1. As expected, Senfroth 516 is seen to be a stronger frother than 1-pentanol: higher amounts of solids and water were recovered from tests using Senfroth 516 on its own than when using 1-pentanol on its own. The mass of solids recovered increased by nearly 50% (from 12.4 g to 18.3 g) and the amount of water by nearly 70% (from 207.3 g to 340.2 g) on going from 50 g/t pentanol frother to 50 g/t Senfroth 516.

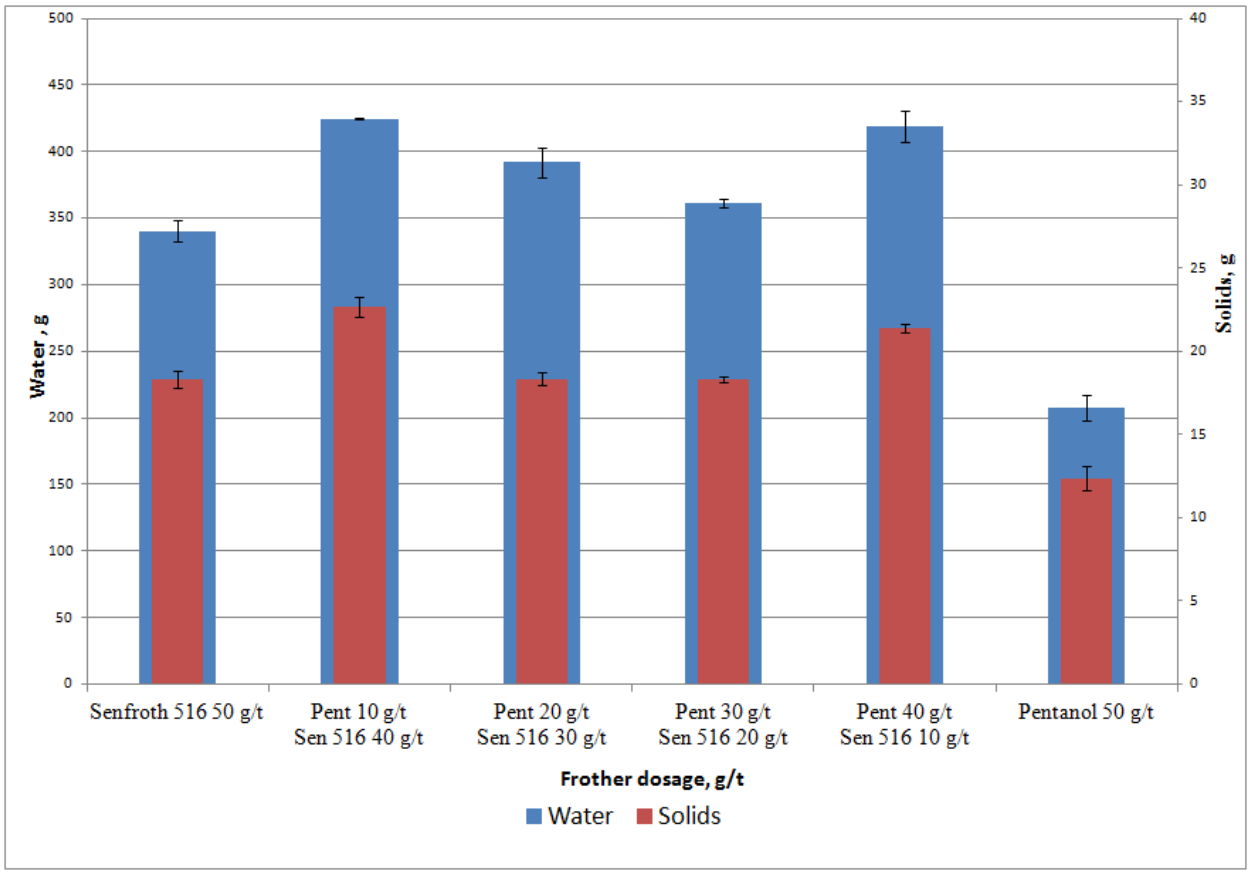

Figure 4.1 Mass of solids and water recovered in flotation tests conducted on Merensky ore #1 using blends of Senfroth 516 and 1-pentanol frothers, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

The blending of Senfroth 516 and pentanol in any ratio (at the same total dosage of 50 g/t) resulted in a higher recovery of solids and water than when using pentanol on its own. The highest amounts of solids and water were obtained when using blends of 1:4 and 4:1. These amounts were higher even than when using Senfroth 516 on its own, suggesting that the addition of a small amount of either frother to the other results in a synergistic effect.

It is interesting to note that the amount of solids recovered from tests using blends of the two frothers at ratios of 2:3 and 3:2 were virtually identical to using Senfroth 516 on its own. The recovery of water, however, increased upon blending of the frothers. As solids recovery by entrainment is proportional to water recovery it would be expected that the solids recovery would have increased as well. This suggests that any increase in recovery by entrainment was matched by an equivalent loss in recovery by true flotation.

Further analysis of the flotation performance when using the frother blends was carried out by determining the recoveries and grades of the valuable minerals in the concentrates. Feeds, concentrates and tails were filtered, dried, weighed and analysed for copper, nickel and sulphur. The recoveries of these sulphide minerals in the concentrate are assumed to give an indication of PGM recovery due to the strong association between the sulphides and the PGMs in the Merensky reef, as explained in section 1.4.3.

Figure 4.2 plots the copper grade against the copper recovery for all the tests. The highest recoveries were obtained from the tests using Senfroth 516/1-pentanol blends in the ratios 1:4 and 4:1.The highest recovery of 87.1% was obtained with the 4:1 polyglycol/alcohol blend, with a grade of 3.1% copper. Higher grades were obtained from the tests using the frothers in their pure forms, but at the lowest recoveries (the recovery obtained with pure Senfroth 516 was around 80%). The Senfroth 516/1-pentanol blends in ratios 2:3 and 3:2 produced higher recoveries than the pure frothers, but not as high as with the 1:4 and 4:1 blends. Similar trends were observed for nickel and sulphur, as shown in Figures 4.3 and Figure 4.4.

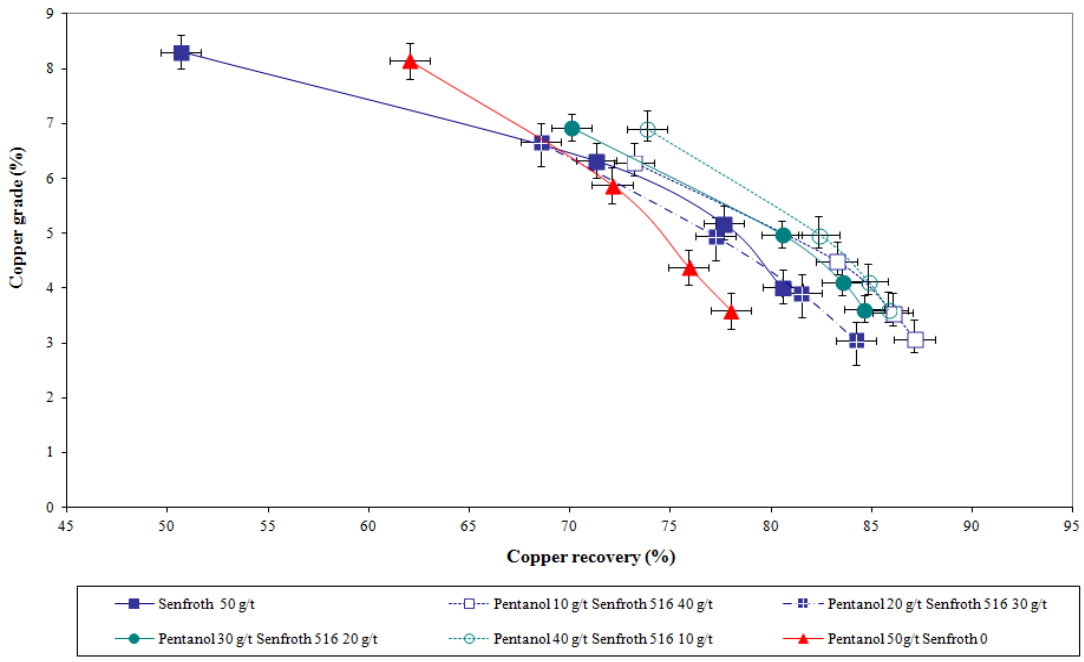

Figure 4.2 Copper grade vs copper recovery for tests conducted on Merensky ore #1 using blends of Senfroth 516 and 1-pentanol frothers, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

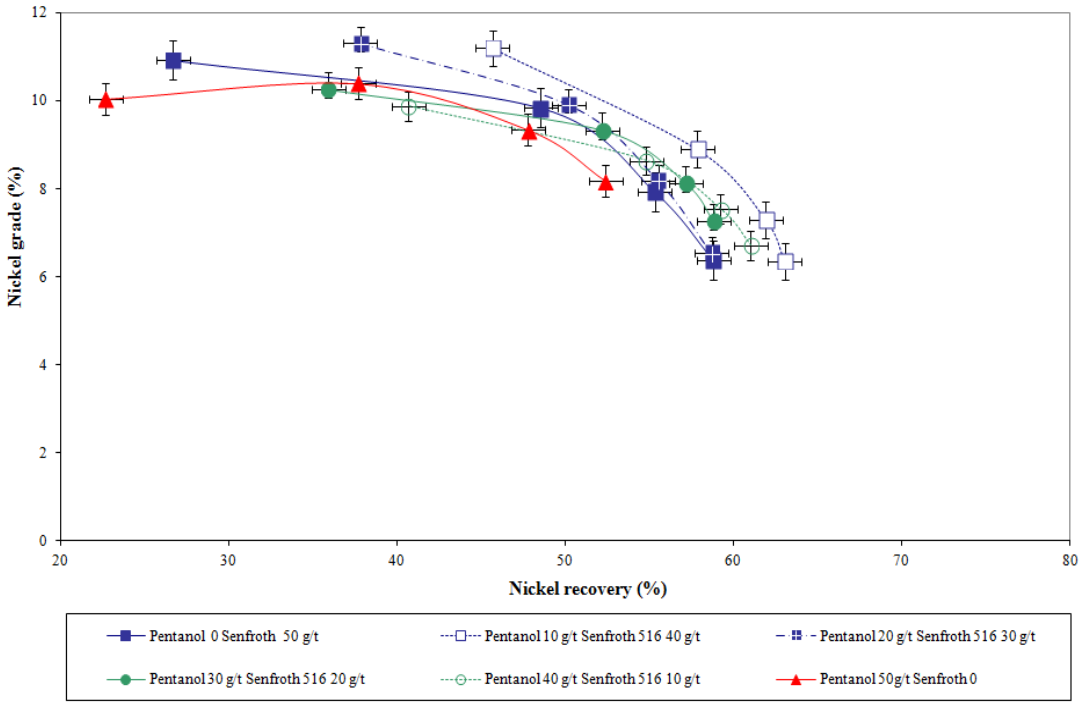

Figure 4.3 Nickel grade vs nickel recovery for tests conducted on Merensky ore #1 using blends of Senfroth 516 and 1-pentanol frothers, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

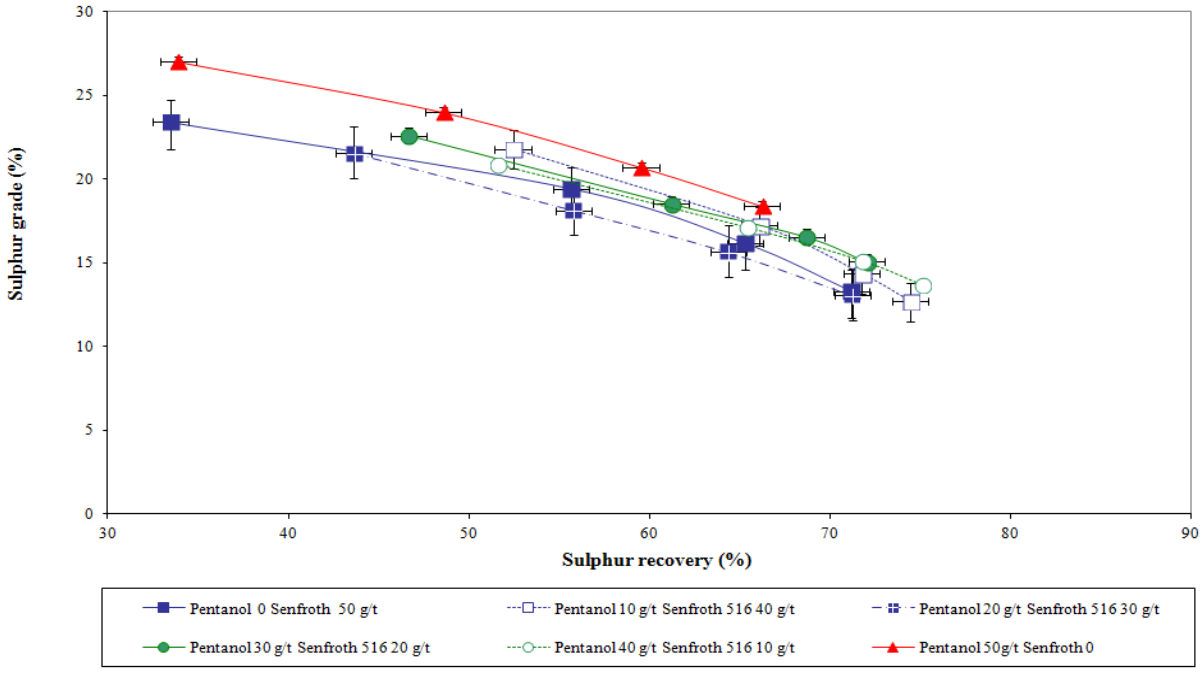

Figure 4.4 Sulphur grade vs sulphur recovery for tests conducted on Merensky ore #1 using blends of Senfroth 516 and 1-pentanol frothers, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

On the basis of these results it was concluded that the frother blends were producing higher recoveries of both copper and nickel than the pure frothers, accompanied in most instances by high grades. It was therefore decided to conduct the main program of flotation experiments with 1:4 and 4:1 blends of polyglycol and alcohol frothers.

4.3 Main flotation test work

The main flotation test work focused on the polyglycol/alcohol blend ratios that gave the best results from the preliminary testwork, i.e. 4:1 and 1:4. The range of polyglycol frothers investigated was expanded to include the commercially available polyglycols Dow 200 and Dow 250. The range of alcohol frothers was also increased to include1-hexanol and the commercially available methyl isobutyl carbinol (MIBC). Firstly, flotation tests were carried out using the frothers individually in their pure forms and then in their blends.

4.3.1 Pure frothers

Figure 4.5 shows the final solids and water recoveries from flotation tests conducted on Merensky ore #1 using 1-pentanol,1-hexanol, MIBC, Senfroth 516, Dow 200 and Dow 250 individually, at a dosage of 50 g/t. As expected, the polyglycols are seen to be stronger frothers than the alcohols: higher amounts of solids were recovered from tests using Dow 200 and Dow 250 (in particular) than from tests using any of the alcohol frothers. The mass of solids recovered increased by more than 100% (from 12.4 g to 26.6 g) on going from 50 g/t pentanol frother to 50 g/t Dow 250.

For the alcohol frothers, the solids recovery increased in the order of 1-pentanol < 1-hexanol < MIBC, while for the polyglycols the solids recovery increased in the order Senfroth 516 < Dow 200 < Dow 250, with the results for Dow 200 and Dow 250 being very similar. The solids recovery using Senfroth 516 was not dissimilar from that using MIBC.

The mass of water recovered increased by nearly 90% (from 207.3 g to 388.3 g) on going from 50 g/t pentanol frother to 50 g/t Dow 250. However, except for the test with 1-pentanol, the water recoveries were not too dissimilar when using the individual frothers: the values for 1-hexanol, Senfroth 516 and Dow 200 were within experimental error of each other (around 340 g to 350 g), while the water recovery obtained when using MIBC was higher (382.6 g),

approaching that obtained when using Dow 250. This is interesting as the solids recoveries were significantly higher when using the Dow frothers.

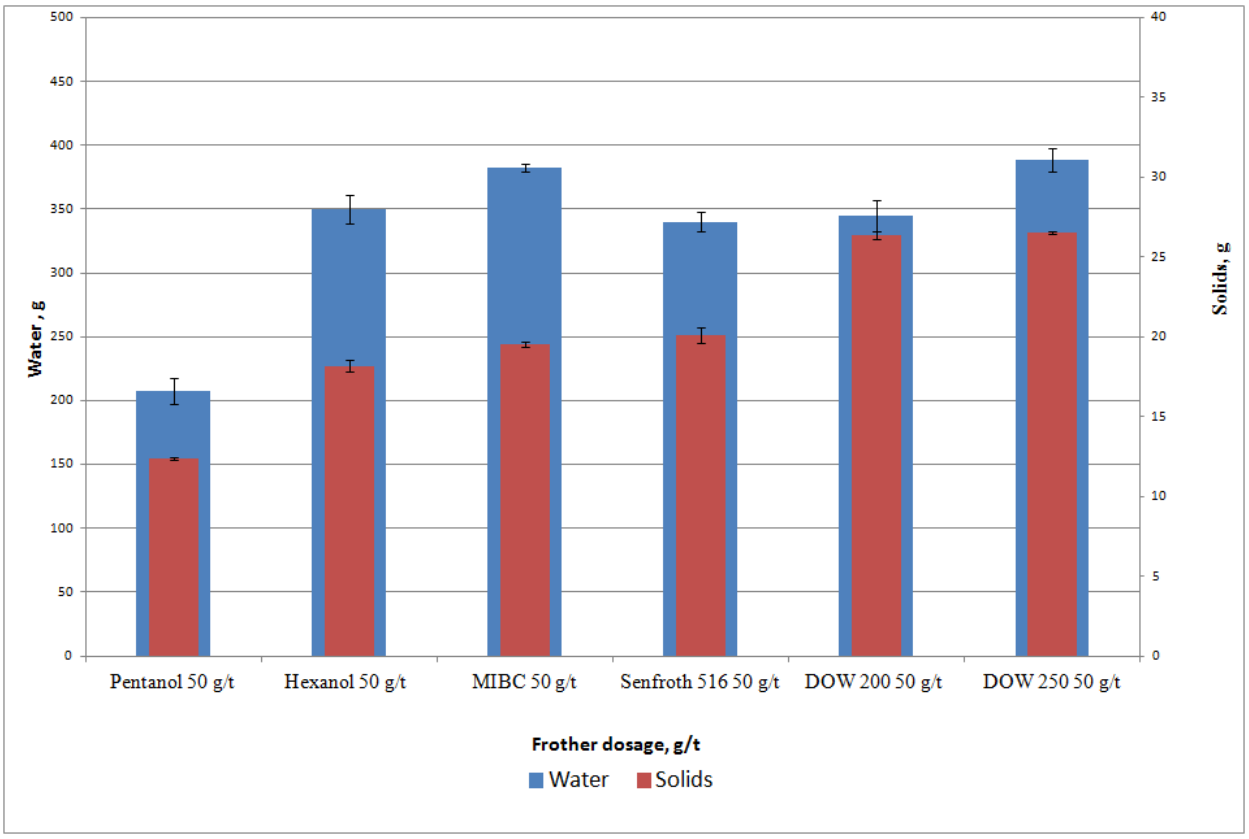

Figure 4.5 Mass of solids and water recovered in flotation tests conducted on Merensky ore #1 using pure frothers only, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

Further analysis of the flotation performance when using the individual frothers was carried out by determining the recoveries and grades of the valuable minerals in the concentrates. Figure 4.6 plots the copper grade against copper recovery for the individual frothers. As seen in the preliminary work (Figure 4.2), the highest recoveries were obtained from the tests using polyglycol frothers, particularly Dow 200 and Dow 250, which also produced the best grades. The highest recovery of 85.6% was obtained when using Dow 250, with a grade of 3.8 % copper. Similar trends were observed for nickel and sulphur results as shown in Figure 4.7 and Figure 4.8. Results for Senfroth 516 were always between the alcohols and the rest of the polyglycols.

It was therefore dropped from the list of polyglycols for the rest of the experiments.

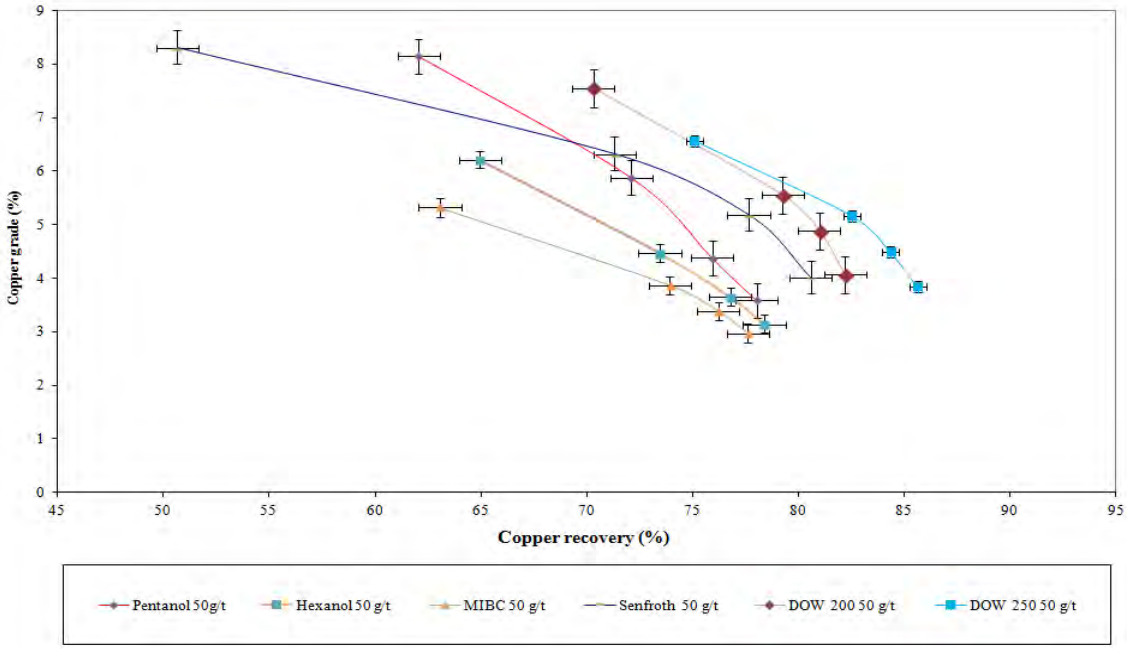

Figure 4.6 Copper grade vs copper recovery for tests conducted on Merensky ore #1 using pure frothers, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

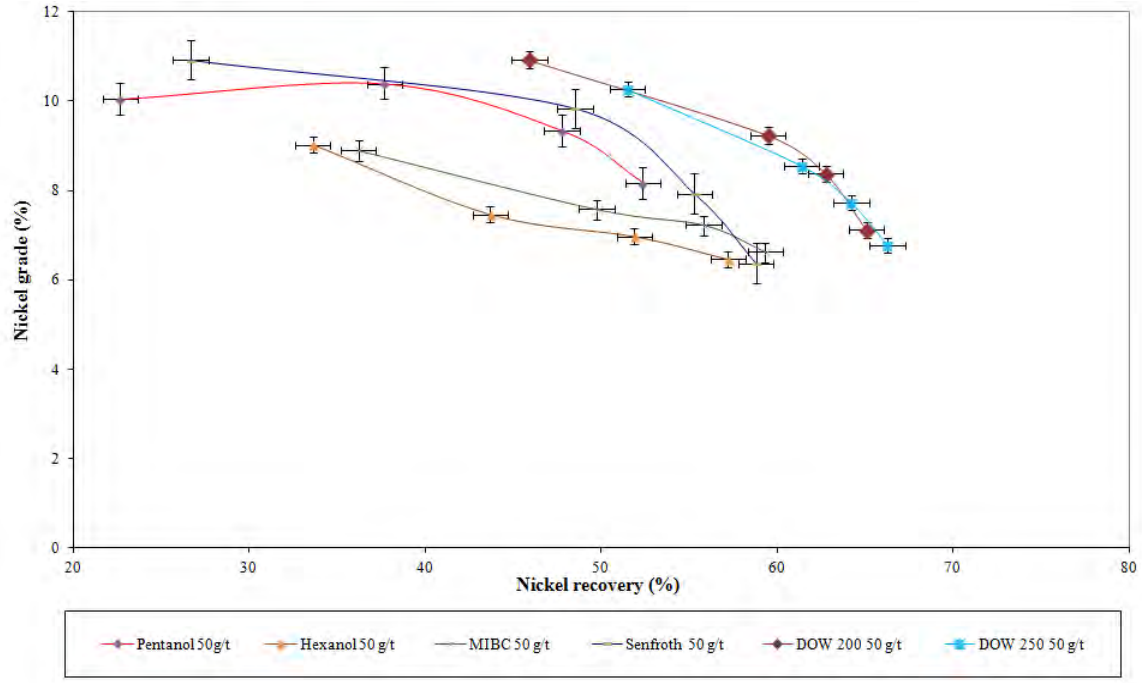

Figure 4.7 Nickel grade vs nickel recovery for tests conducted on Merensky ore #1 using pure frothers, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

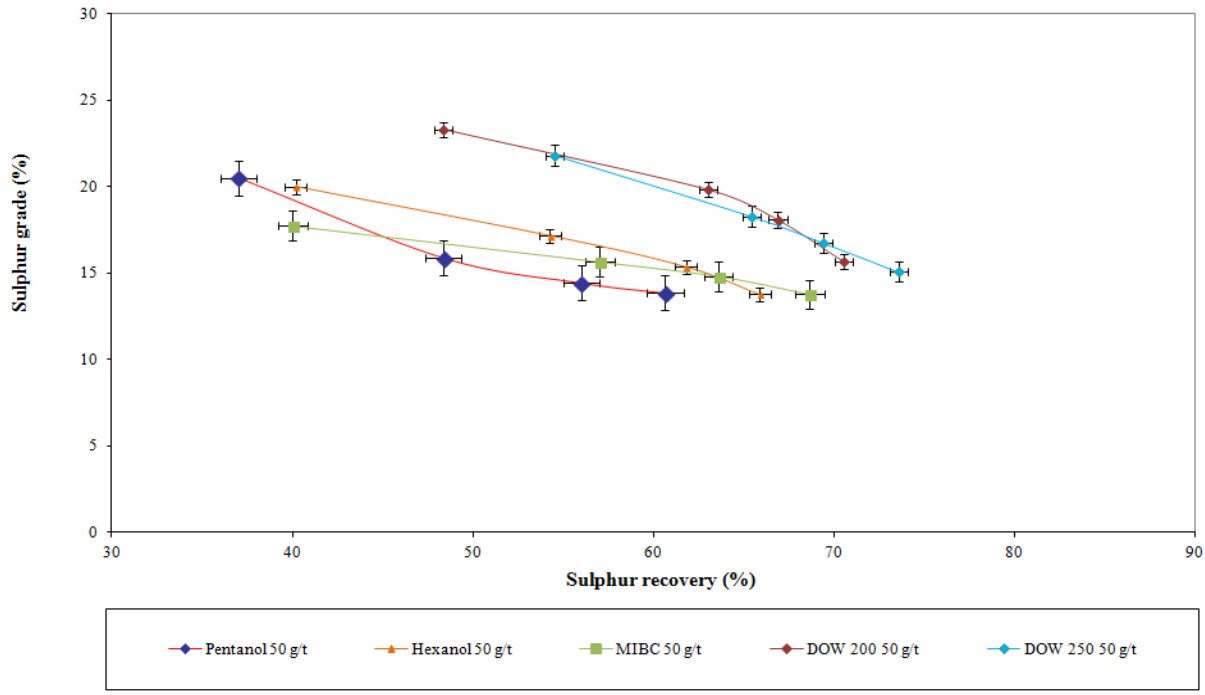

Figure 4.8 Sulphur grade vs sulphur recovery for tests conducted on Merensky ore #1 using pure frothers, at a total frother dosage of 50 g/t(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

4.3.2 Batch flotation of ore # 1 with blends of polyglycol and alcohol at a ratio of 1:4

The results of experiments using blends of polyglycol/alcohol frothers in the ratio of 1:4 are shown in Figures 4.9 to 4.12, for the flotation tests conducted on Merensky ore #1. Figure 4.9 shows the final solids and water recoveries obtained, and includes the results from the tests using the alcohol frothers individually, for comparison. As noted in Figure 4.5, both solids and water recoveries increased in the order 1-pentanol < 1-hexanol < MIBC in case of the individual alcohols; upon addition of polyglycol frother, the same trend was maintained, but with higher water and solids recoveries being achieved than when using any of the alcohol frothers individually.

The mass of solids recovered increased by nearly 60% (from 12.4 g to 20.6 g) and the amount of water nearly 70% (from 207.3 g to 350.2 g) on the addition of Dow 200 frother to 1-pentanol and by nearly 70% (to 21.8 g) and 60% (to 388.9 g), respectively on the addition of Dow 250. Similar trends were observed on the addition of Dow 200 and Dow 250 to 1-hexanol as well as MIBC. Water recovery was much higher with the 6-carbon alcohols (hexanol, MIBC) than with

pentanol in all cases, with MIBC producing the highest water recovery either on its own or in blends.

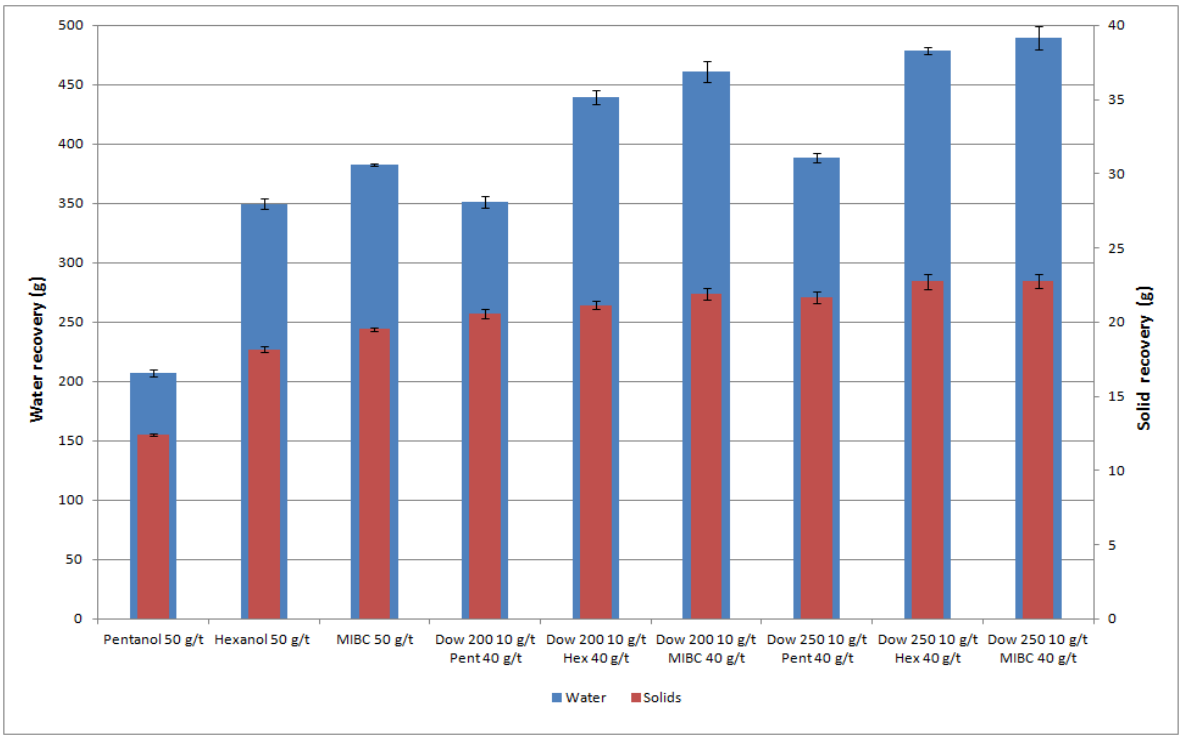

Figure 4.9 Mass of solids and water recovered in flotation tests conducted on Merensky ore #1 using 1-pentanol, 1-hexanol and MIBC in blends with Dow 200 and Dow 250, as well as the alcohols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

Figure 4.10 plots the copper grade against copper recovery for the same tests. It is clear from the figure that the poorest recoveries were obtained from the tests conducted using MIBC and pentanol in their pure forms. The addition of Dow 200 or Dow 250 increased the copper recoveries by between 6 and 8%, while maintaining the grade at around 3%. Higher results were obtained using Dow 200/Dow 250 blends with hexanol/MIBC than with pentanol.

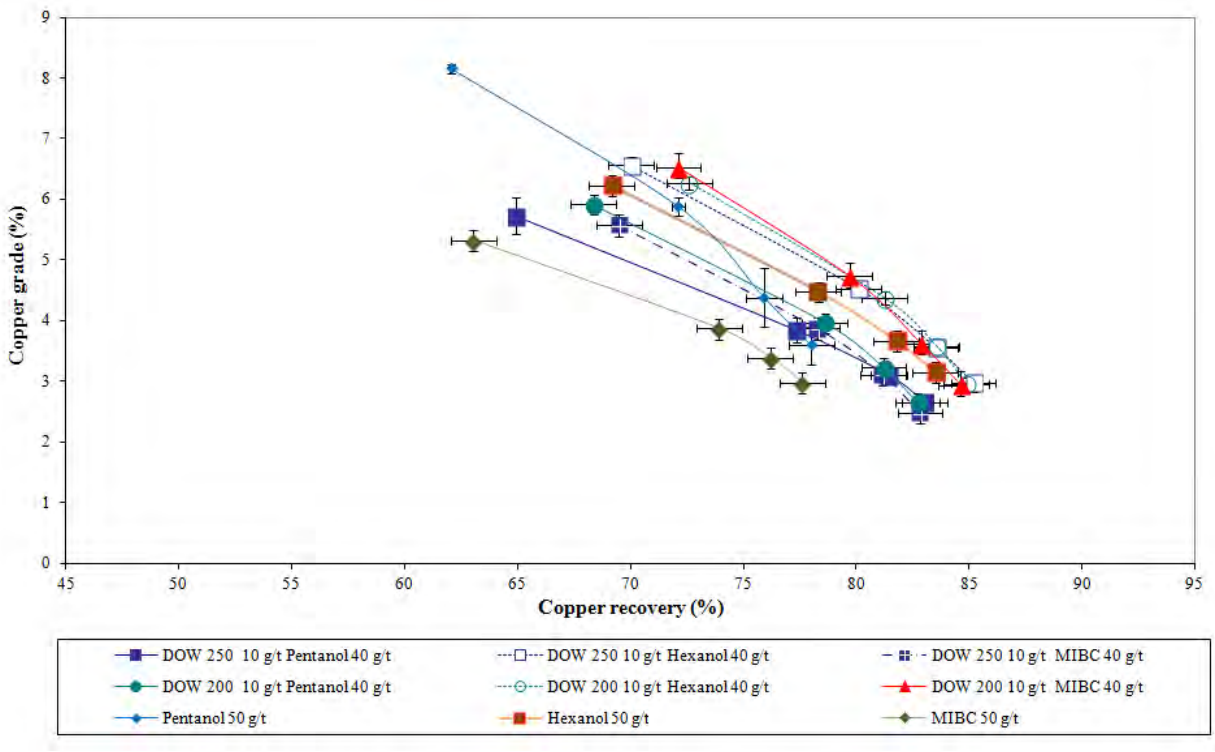

Figure 4.10 Copper grade vs copper recovery for tests conducted on Merensky ore #1 using blends of 1-pentanol, 1-hexanol and MIBC with Dow 200 and Dow 250 as well as the alcohols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

Nickel grades versus recoveries for these tests are shown in Figure 4.11. The poorest recoveries were obtained from the tests conducted using pure pentanol; addition of Dow 200 or Dow 250 greatly improved the nickel recoveries. The best recoveries were obtained from the tests conducted using blends of Dow 250/hexanol (62.7%) (at a grade of 6.0%) and Dow 250/MIBC (61.0%) (at a grade of 6.3%). The sulphur grades and recoveries for these tests are shown in Figure 4.12. The results show the same trends with the use of blends resulting in higher recoveries than pure frothers. Higher recoveries in this case were obtained from the blends of Dow 250/MIBC (74.4 %), Dow 200/pentanol (74.1%) and Dow 200/MIBC (72.4%). The sulphur grades for these tests were around 12%.

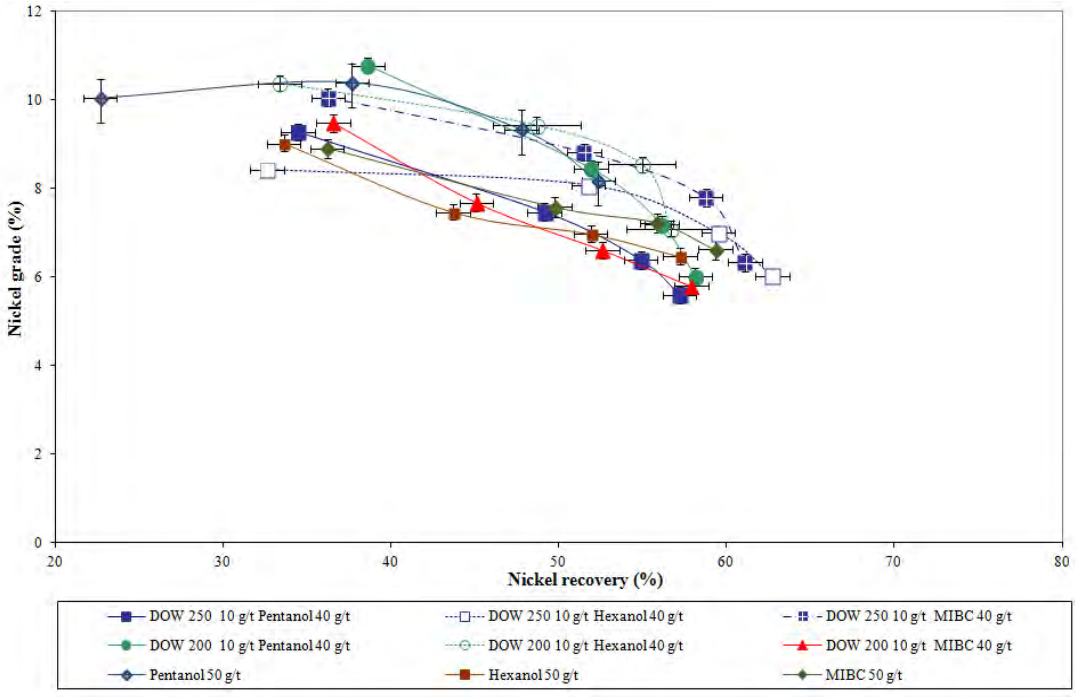

Figure 4.11 Nickel grade vs nickel recovery for tests conducted on Merensky ore #1 using blends of 1-pentanol, 1-hexanol and MIBC with Dow 200 and Dow 250 as well as the alcohols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

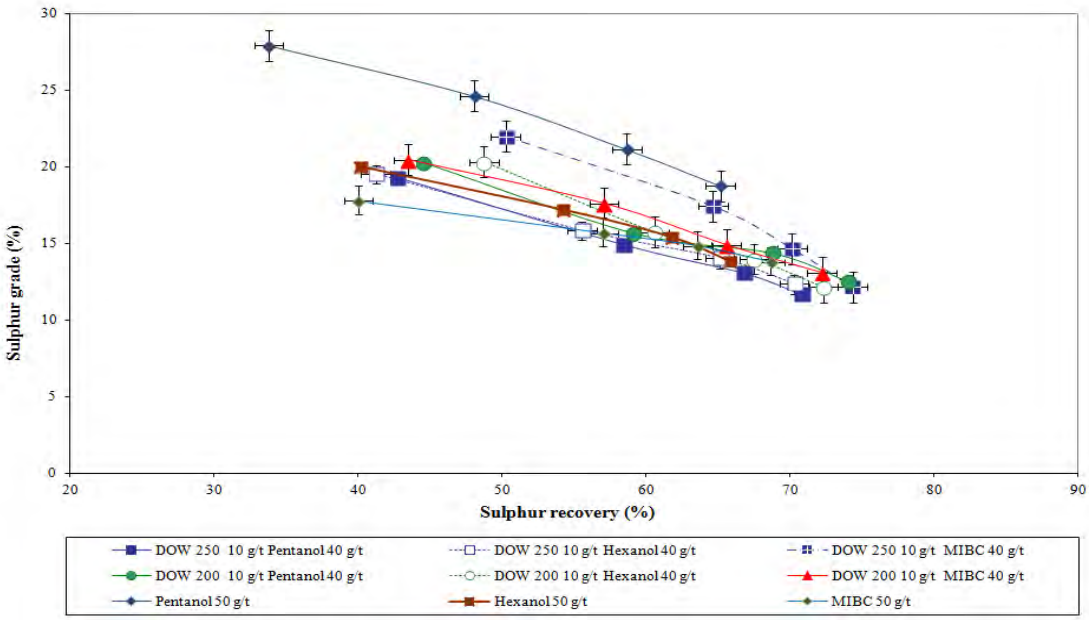

Figure 4.12 Sulphur grade vs sulphur recovery for tests conducted on Merensky ore #1 using blends of 1-pentanol, 1-hexanol and MIBC with Dow 200 and Dow 250 as well as the alcohols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

4.3.3 Batch flotation of ore # 1 with blends of polyglycol and alcohol at a ratio of 4.1

As before, the use of frother blends with polyglycol/alcohol ratio of 4:1 resulted in higher water and solids recoveries than obtained with the polyglycol frothers on their own. The trends were as seen previously when small amounts of polyglycol frother was blended with alcohol, in that the mass of solids and water recovered increased in the order 1-pentanol < 1-hexanol < MIBC. For Dow 200 frother, the mass of solids recovered increased by nearly 30% (from 26.3 g to 32.6 g) and the amount of water nearly 30% (from 344.8 g to 445.4 g) on the additional of MIBC frother; for Dow 250 frother, the mass of solids recovered increased by nearly 40% (from 26.55 g to 35.1 g) and the amount of water by nearly 30% (from 388.3 g to 478.4 g). The same trend was observed when Dow 250 or Dow 200 were blended with 1-pentanol or 1-hexanol.

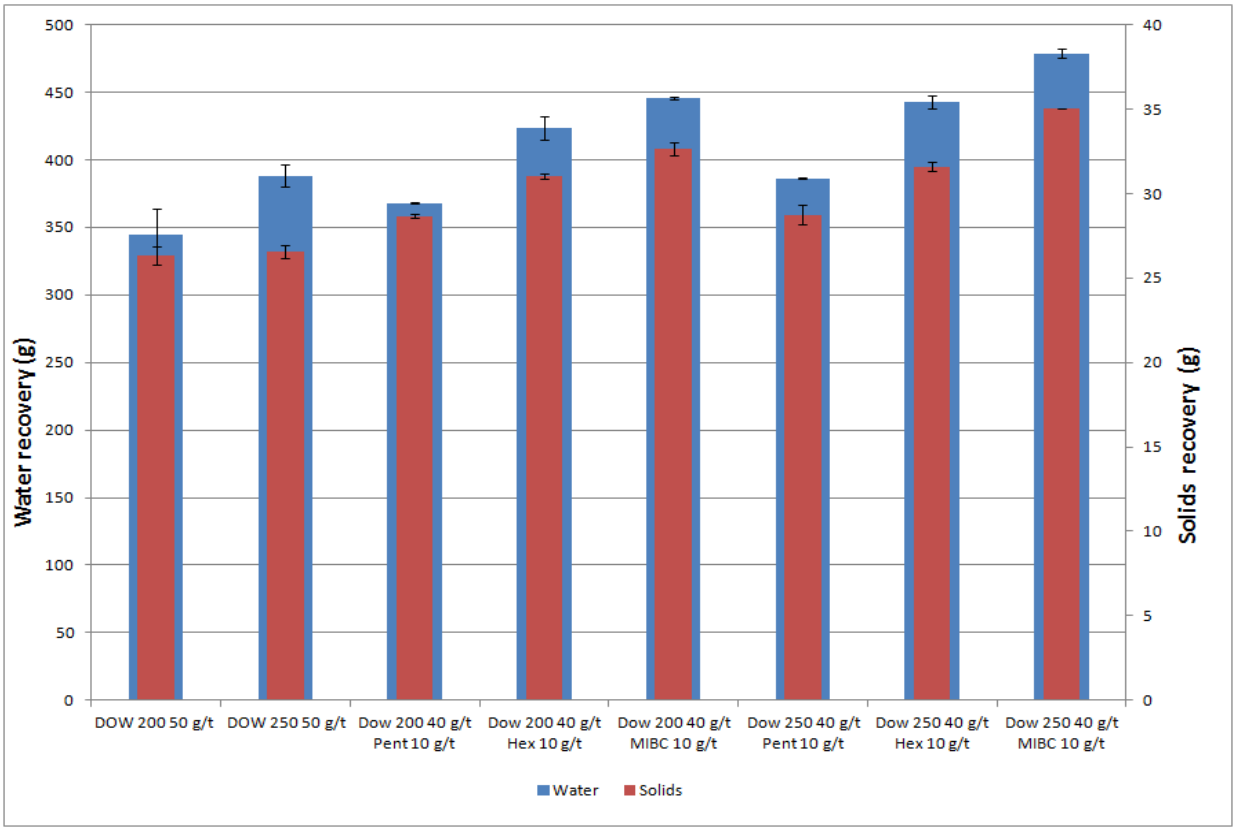

Figure 4.13 Mass of solids and water recovered in flotation tests conducted on Merensky ore #1 using Dow 200 and Dow 250 in blends with 1-pentanol, 1-hexanol and MIBC, as well as the polyglycols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

Figure 4.14 plots the copper grade against the copper recovery for this series of experiments. The highest recoveries were obtained from the tests in which blends were used; the highest copper recoveries were obtained using Dow 250/MIBC (90.7%) and Dow 200/MIBC (90.1%). The highest copper grades were obtained from the same tests (around 4.6%)

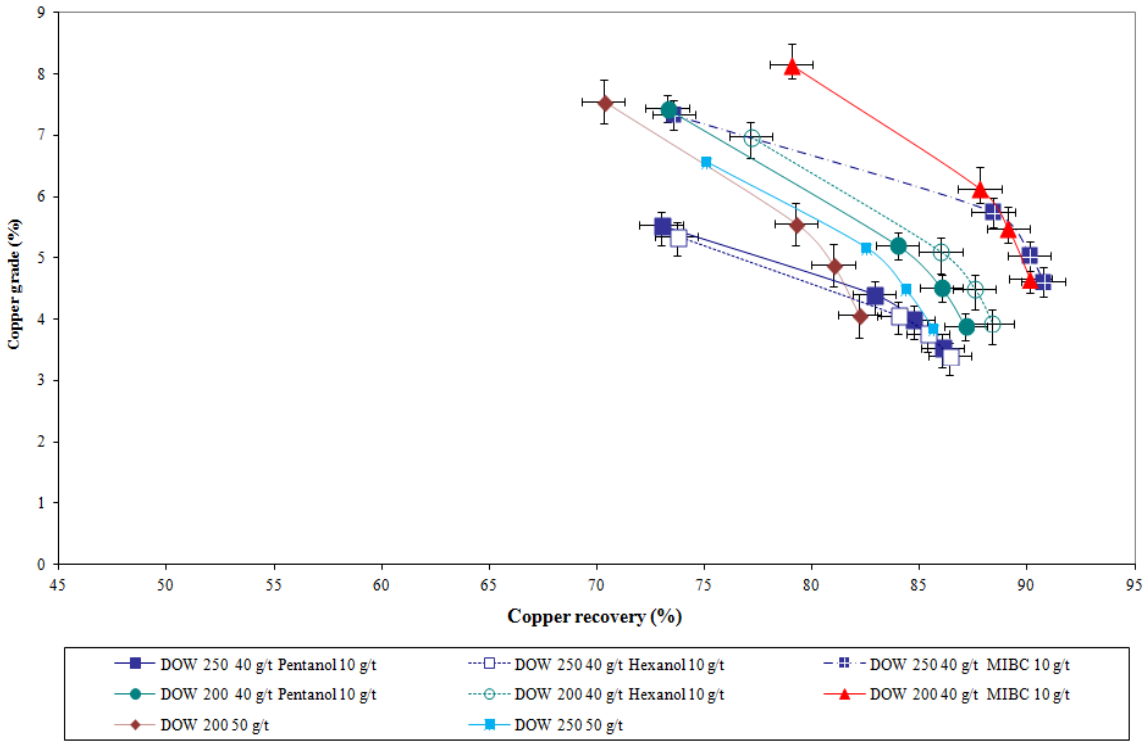

Figure 4.14 Copper grade vs copper recovery for tests conducted on Merensky ore #1 using Dow 200 and Dow 250 in blends with 1-pentanol, 1-hexanol and MIBC, as well as the polyglycols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

The flotation performance of nickel in these tests is shown in Figure 4.15. Once again, the highest recoveries of nickel were obtained from flotation tests conducted using frother blends than from the tests using the frothers in their pure form. As with copper the highest recoveries were obtained using blends of Dow 250/MIBC (75.5%) and Dow 200/MIBC (74.8%), as were the highest grades (8.0% and 8.2% respectively). Figure 4.16 plots sulphur grade versus sulphur recovery and shows that the highest recoveries were obtained from tests using blends of Dow 250/MIBC (80% recovery, 14.7% grade), Dow 200/MIBC (79.3% recovery, 18.1% grade) and Dow 250/1-hexanol (79.1% recovery, 16.2% grade).

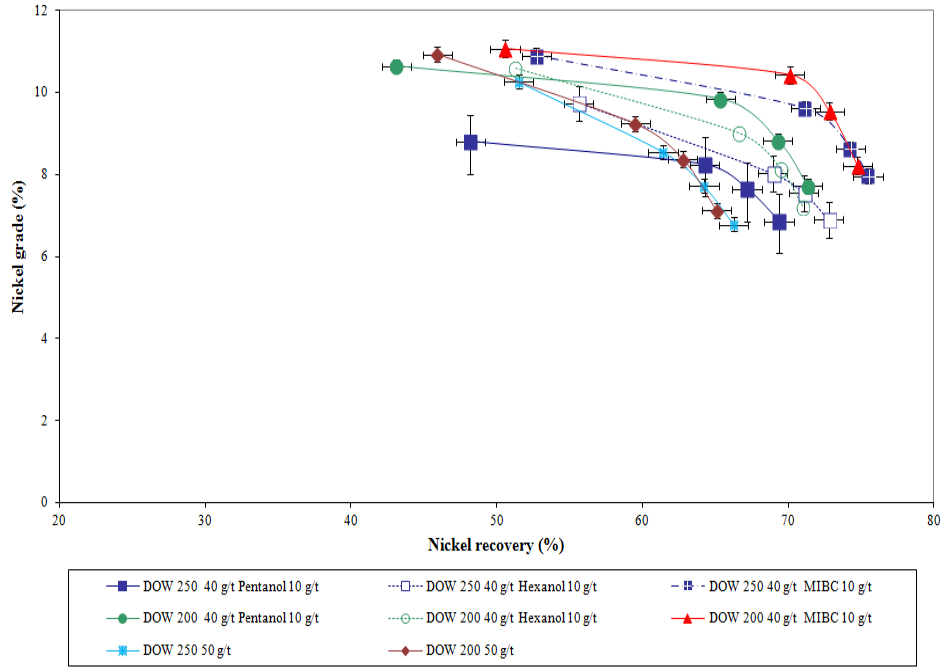

Figure 4.15 Nickel grade vs nickel recovery from flotation tests conducted on Merensky ore #1 using Dow 200 and Dow 250 in blends with 1-pentanol, 1-hexanol and MIBC, as well as the polyglycols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

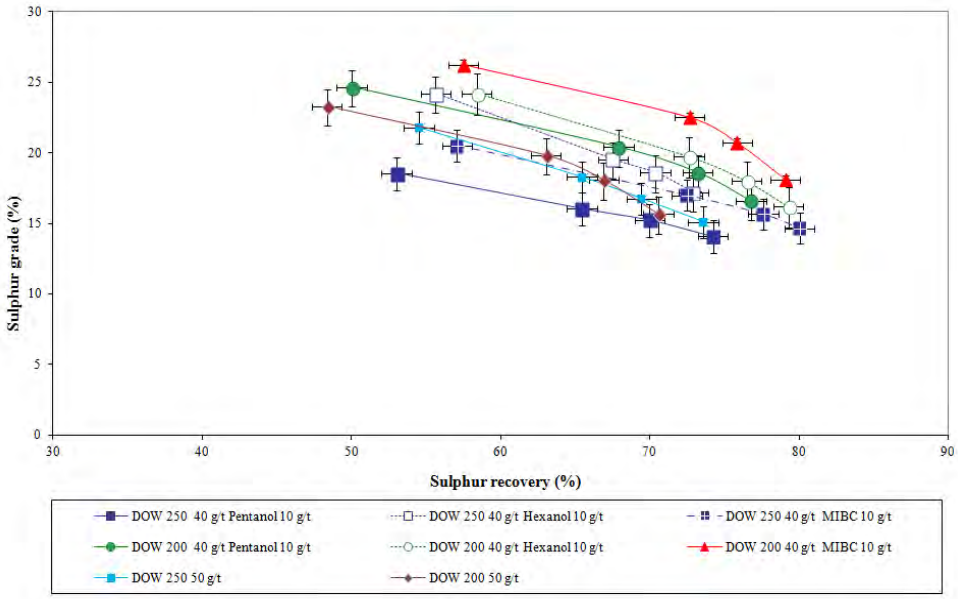

Figure 4.16 Sulphur grade vs sulphur recovery from flotation tests conducted on Merensky ore #1 using Dow 200 and Dow 250 in blends with 1-pentanol, 1-hexanol and MIBC, as well as the polyglycols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

4.3.4 Summary of the results

Selected recovery results from some of the experiments conducted on Merensky ore # 1 are shown in Figures 4.17 to 4.20. The selected experiments are those using MIBC, Dow 200 and Dow 250 in their pure form and blended in the ratios of 1:4 and 4:1. Figure 4.17 shows mass of solids and water recovered for these tests. It can clearly be seen that more mass of solid and water is recovered from the tests conducted at the ratio of 4:1 (polyglycol/alcohol) compared to experiments conducted at the ratio of 1:4. Dow 200/MIBC blend for example, mass of solid recovered increased from 21.88 g when tests were conducted with blends of polyglycol and alcohol at a ratio of 1.4 to 28.75g when tests were conducted with blends of polyglycol and alcohol at a ratio of 4.1 (more than 30%). Mass of water recovered on the other hand was relatively similar (388.7g to 386.34g).

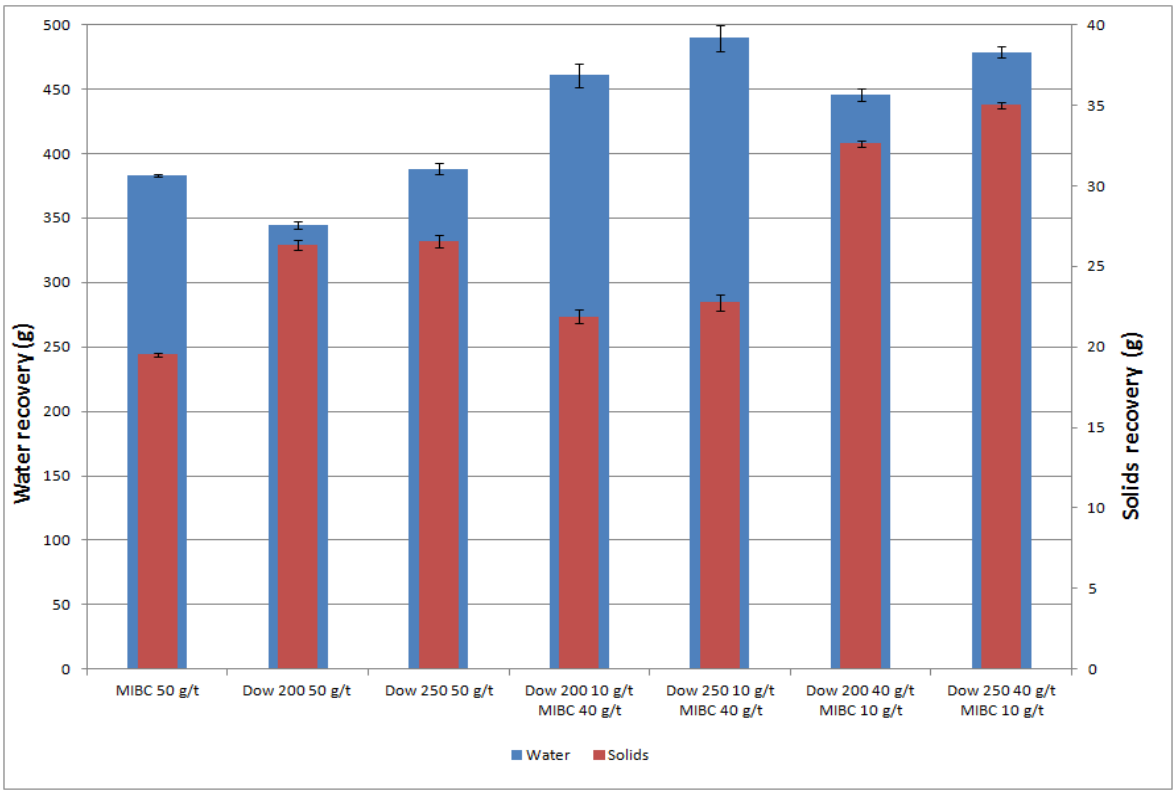

Figure 4.17 Mass of solids and water recovered from selected flotation tests conducted on Merensky ore #1 using Dow 200 and Dow 250 in blends with MIBC, as well as the frothers in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

Figure 4.18 shows the copper grade vs copper recovery results. As noted in previous sections, when used in their pure forms, Dow 250 frother produced the highest copper recovery followed by Dow 200 and MIBC. Upon blending of MIBC with Dow 200 and Dow 250 in the ratio of 1:4 (polyglycol/alcohol), the copper recoveries increased by more than 5%. But on blending in the ratio of 4:1, the recoveries increased by more than 15% relative to pure MIBC and by more than 6% relative to Dow 200 or Dow 250 used individually. The same trends were observed for nickel and sulphur, as shown in Figure 4.19 and Figure 4.20.

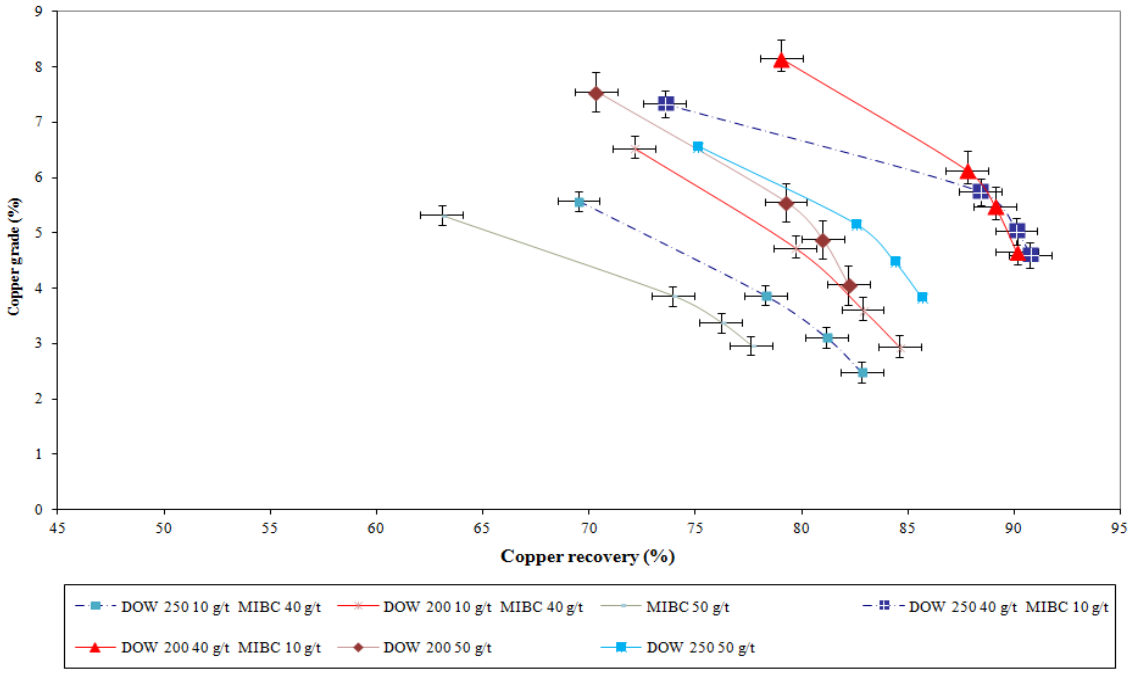

Figure 4.18 Copper grade vs copper recovery from selected flotation tests conducted on Merensky ore #1 using Dow 200 and Dow 250 in blends with MIBC, as well as the frothers in their pure forms, at a total frother dosage of 50 g/t (SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

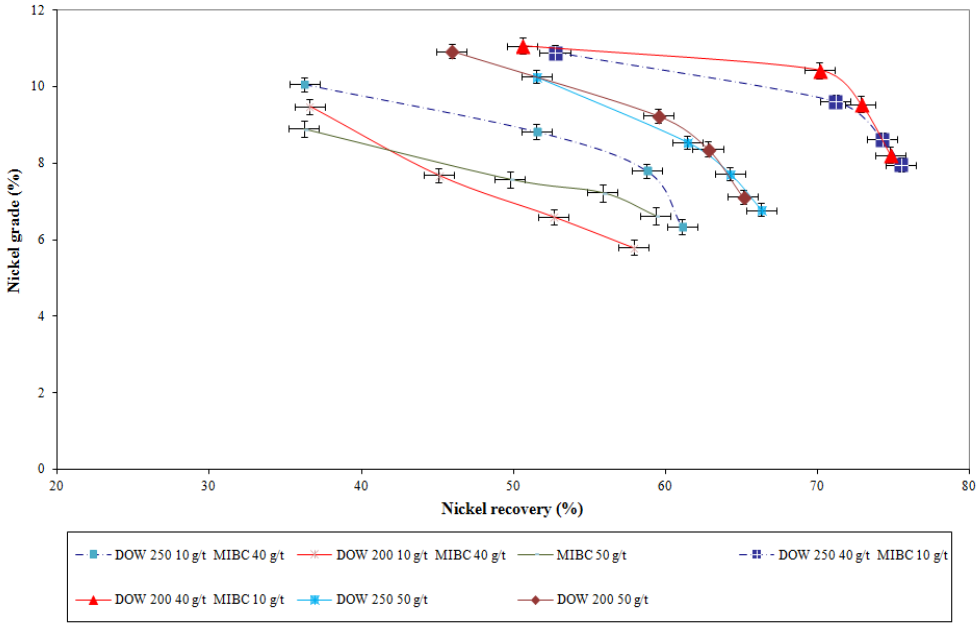

Figure 4.19 Nickel grade vs nickel recovery from selected flotation tests conducted on Merensky ore #1 using Dow 200 and Dow 250 in blends with MIBC, as well as frothers in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

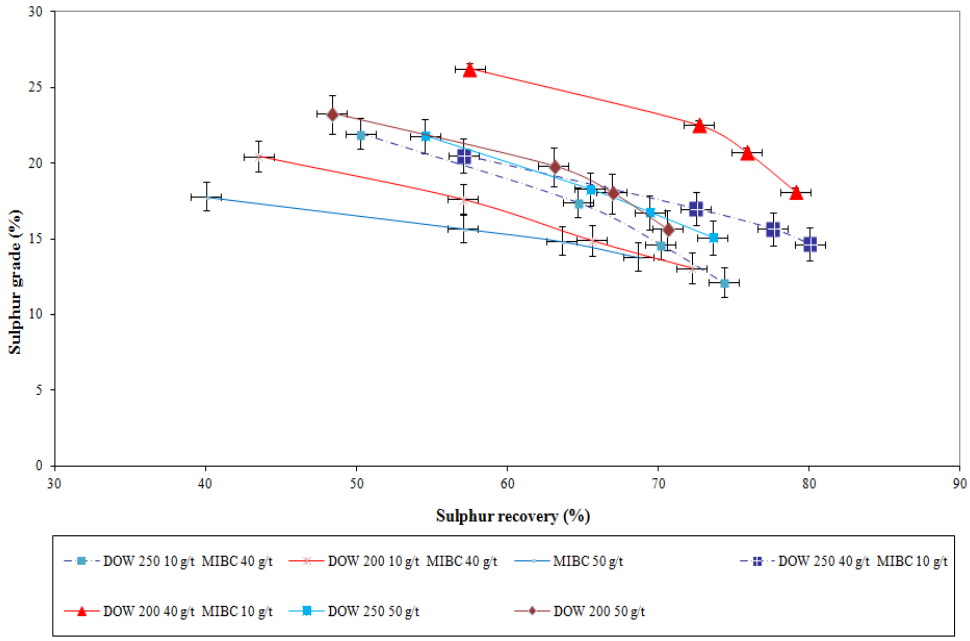

Figure 4.20 Sulphur grade vs sulphur recovery from selected flotation tests conducted on Merensky ore #1 using Dow 200 and Dow 250 in blends with MIBC, as well as the frothers in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

In summary, the flotation tests with Merensky ore #1 using polyglycol/alcohol frother blends in the ratio of 4:1 always gave higher recoveries when compared with blends in the ratio 1:4, or

with pure alcohols or polyglycols used individually. These recoveries were always accompanied by high copper, nickel and sulphur grades.

Consequently, for the next set of experiments, using Merensky ore #2, it was decided to proceed with the blend ratio that gave the best results, 4:1. The results of this work are presented in the following section.

4.3.5 Batch flotation of ore # 2 with blend of polyglycol and alcohol at a ratio of 4.1

Batch flotation experiments were conducted using the second Merensky ore sample under conditions that gave the best results from the previous set of experiments, i.e. with polyglycol/alcohol frothers at the ratio of 4:1. [2]Figure 4.21 shows final solids and water recoveries for these experiments. The results exhibit the same trends as Merensky ore #1, in that the addition of a small amount of alcohol yielded more water and solids recovery than the pure polyglycols. The trend of 1-pentanol < 1-hexanol < MIBC was again observed. The use of Dow 250 in blends with 1-hexanol and MIBC resulted in higher solids recovery accompanied by slight increases in water recovery in comparison with the use of Dow 200. On the additional of MIBC frother, the mass of solids recovered using Dow 200 frother increased by nearly 17% (from 24.7 g to 28.8 g) and the amount of water nearly 24% (from 375.2 g to 464.6 g). For Dow 250 frother, the mass of solids recovered increased by nearly 23% (from 25.9 g to 31.7 g) and the amount of water by nearly 24% (from 390.3 g to 480.9 g). The same trend was observed for the Dow 200/Dow 250 blends with 1-pentanol and 1-hexanol.

[2] In general, lower solids recoveries were obtained with ore #2, while water recoveries were slightly higher, compared with ore #1

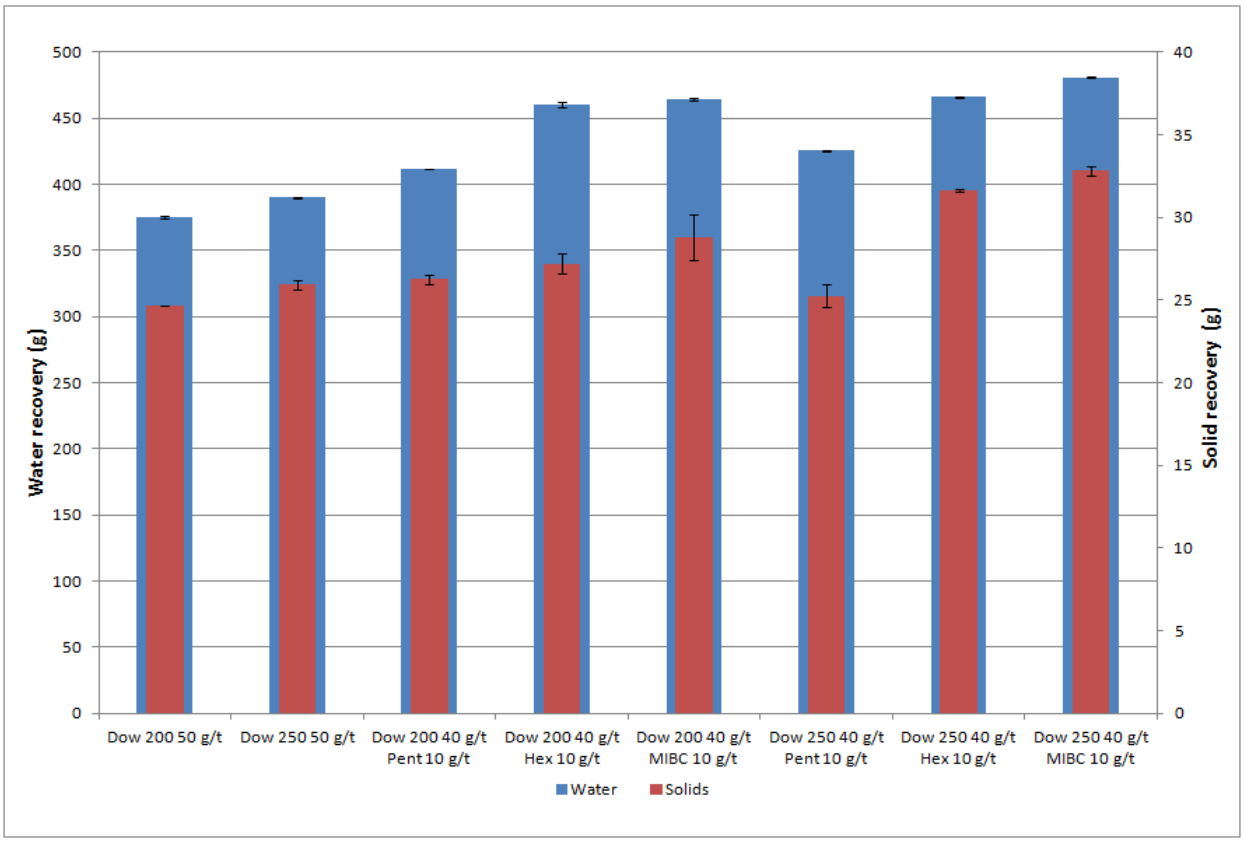

Figure 4.21 Mass of solids and water recovered in flotation tests conducted on Merensky ore #2 using Dow 200 and Dow 250 in blends with 1-pentanol, 1-hexanol and MIBC, as well as the polyglycols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

Figure 4.22 shows the flotation performance of copper for this series of experiments. Similar to ore # 1, the highest recoveries were obtained from the tests in which blends were used; the highest copper recoveries were obtained using Dow 250/MIBC (86%), Dow 200/MIBC (83.5%) and Dow 250/hexanol (83.3%). The highest copper grades were obtained from the same tests (around 3%).

Results for nickel grade versus recovery are shown in Figure 4.23. Again, the highest recoveries of nickel were obtained from flotation tests conducted using blends of Dow 250/MIBC (67.4%), Dow 250/hexanol (66.5%) and Dow 200/MIBC (64.1%). The same tests yielded the highest grades (5.1%, 4.9% and 4.2% respectively).

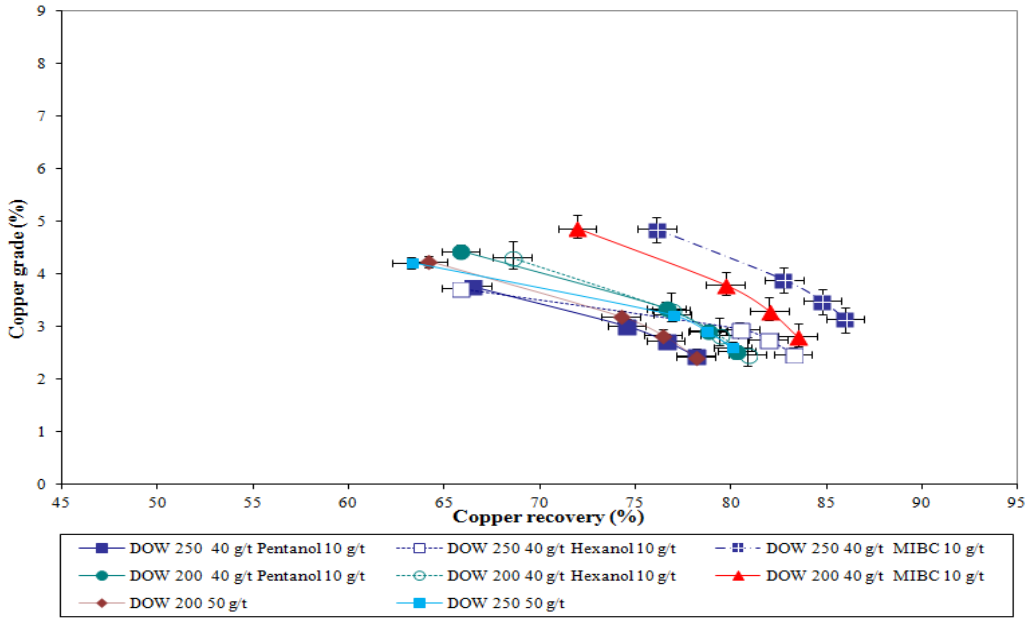

Figure 4.22 Copper grade vs copper recovery for tests conducted on Merensky ore #2 using Dow 200 and Dow 250 in blends with 1-pentanol, 1-hexanol and MIBC, as well as the polyglycols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

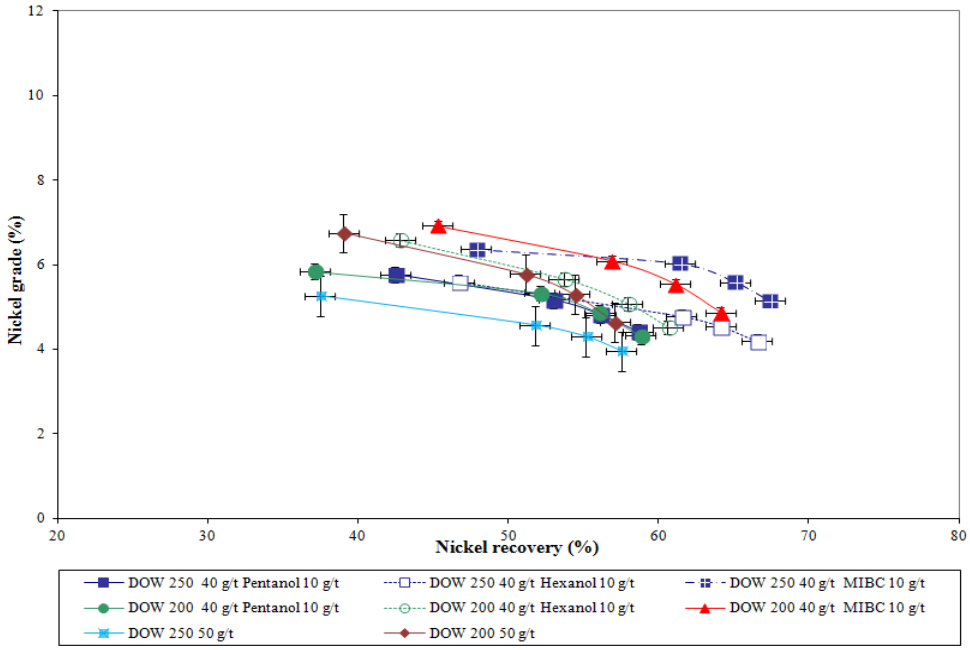

Figure 4.23 Nickel grade vs nickel recovery from flotation tests conducted on Merensky ore #2 using Dow 200 and Dow 250 in blends with 1-pentanol, 1-hexanol and MIBC, as well as the polyglycols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

Figure 4.24 plots the sulphur grade against sulphur recovery for these experiments. It shows that the highest recoveries were obtained from tests conducted using blends of Dow 250/MIBC (80% recovery, 10.94% grade), Dow 200/MIBC (78.4% recovery, 12.1% grade), Dow 200/1-hexanol (78.3% recovery, 11% grade) and Dow 250/1-hexanol (77.1% recovery, 9.3% grade).

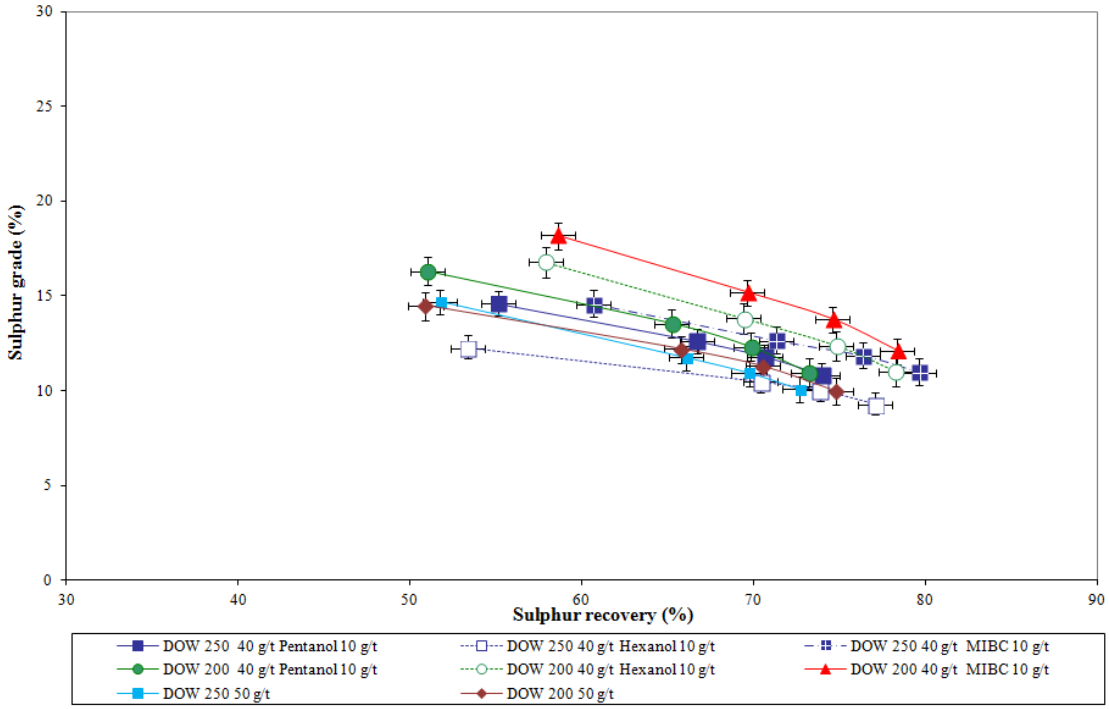

Figure 4.24 Sulphur grade vs sulphur recovery from flotation tests conducted on Merensky ore #1 using Dow 200 and Dow 250 in blends with 1-pentanol, 1-hexanol and MIBC, as well as the polyglycols in their pure forms, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 250 g/t)

In summary, the results obtained for both ores showed that the highest copper, nickel and sulphur recoveries were obtained from tests using blends of Dow 200 and Dow 250 with MIBC in the ratio of 4:1 (at a total frother dosage of 50 g/t). These high recoveries were accompanied by high grades. These tests also yielded the highest solids and water recoveries which usually result in increased recovery at the expense of grade. Copper and nickel recoveries from Merensky ore #2 were lower than those obtained from Merensky ore #1.

4.4 Determination of entrainment

Flotation experiments were carried out to determine how much of the additional solids recovery could be attributed to entrainment. These experiments were conducted at a high depressant dosage of 500 g/t in order to depress all natural floatable gangue present in the ores (see section 2.4.3). Under these conditions, the presence of gangue in the concentrates has been assumed to be via entrainment alone. Figure 4.25 shows final solids and water recovered from tests conducted using Merensky ores #1 and #2 with pure Dow 200 at a dosage of 50 g/t and in a blend with MIBC at a ratio of 4:1. It is evident that at this depressant dosage there was an increase in final water recovery for the blend in comparison to that obtained using Dow 200 in its pure form (from 397 g to 476.2 g for Merensky ore #1 and from 386.9 g to 445.4 g for Merensky ore #2). Higher water recoveries were obtained from tests conducted on Merensky ore #1 (476.2 g) compared to Merensky ore #2 (445.4 g). However, with pure frother the water recoveries for both ores at this depressant dosage were very similar. Higher solids recoveries were observed when using frother blend in comparison to pure Dow 200, with the increase being more pronounced for Merensky ore # 1 (27.2%, from 13.8 g to 17.5 g).

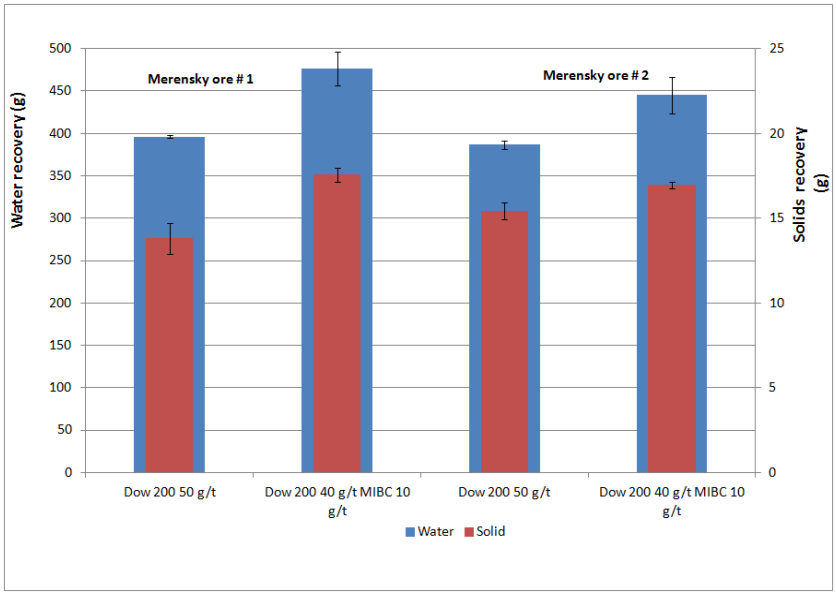

Figure 4.25 Mass of solids and water recovered in flotation tests conducted on Merensky ore #1 and #2 using Dow 200 in its pure form and in blends MIBC, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 500 g/t)

Figure 4.26 shows the cumulative mass of solids versus water recovered during these laboratory flotation tests. For both ores, higher mass per unit water was recovered from the tests conducted using the frother blend than with the pure frother. Using Dow 200 in its pure form, lower mass per unit water was obtained from the tests conducted on Merensky ore #. The highest water recoveries were obtained using the 4:1 blend of Dow 200/MIBC for both ores and suggest the formation of more stable froths and hence higher solids recoveries.

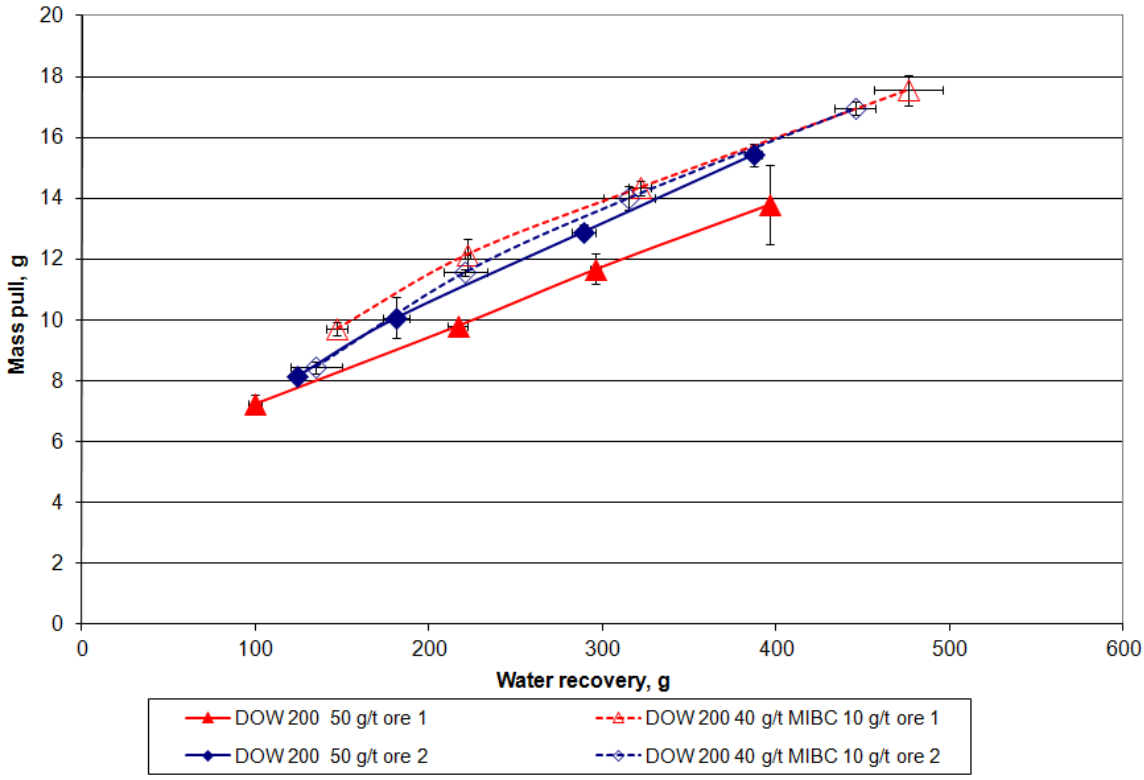

Figure 4.26 Cumulative mass versus water recovered in flotation tests conducted on Merensky ore #1 and #2 using Dow 200 in its pure form and in blends with MIBC, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 500 g/t)

Results for total gangue versus water recovered for all the tests conducted using a depressant dosage of 500 g/t for both ores are shown in Figure 4.27[3]. The results represent both the pure frother and the 4:1 blend of Dow 200/MIBC. The gradient of the line obtained for Merensky ore # 1 represents an entrainment function of 0.0234, which equates to 2.34 g of entrained material

[3] The graph is plotted as explained in section 2.3.4

per 100 ml water recovered. In the same way the entrainment function for Merensky ore # 2 was determined to be 0.0271, which equates to 2.71 g of entrained material per 100 ml water recovered. It is clear from these results that the degree of entrainment is higher for Merensky ore # 2 than ore # 1 under these conditions. This difference may be attributed to differences in the mineralogy between the two ores.

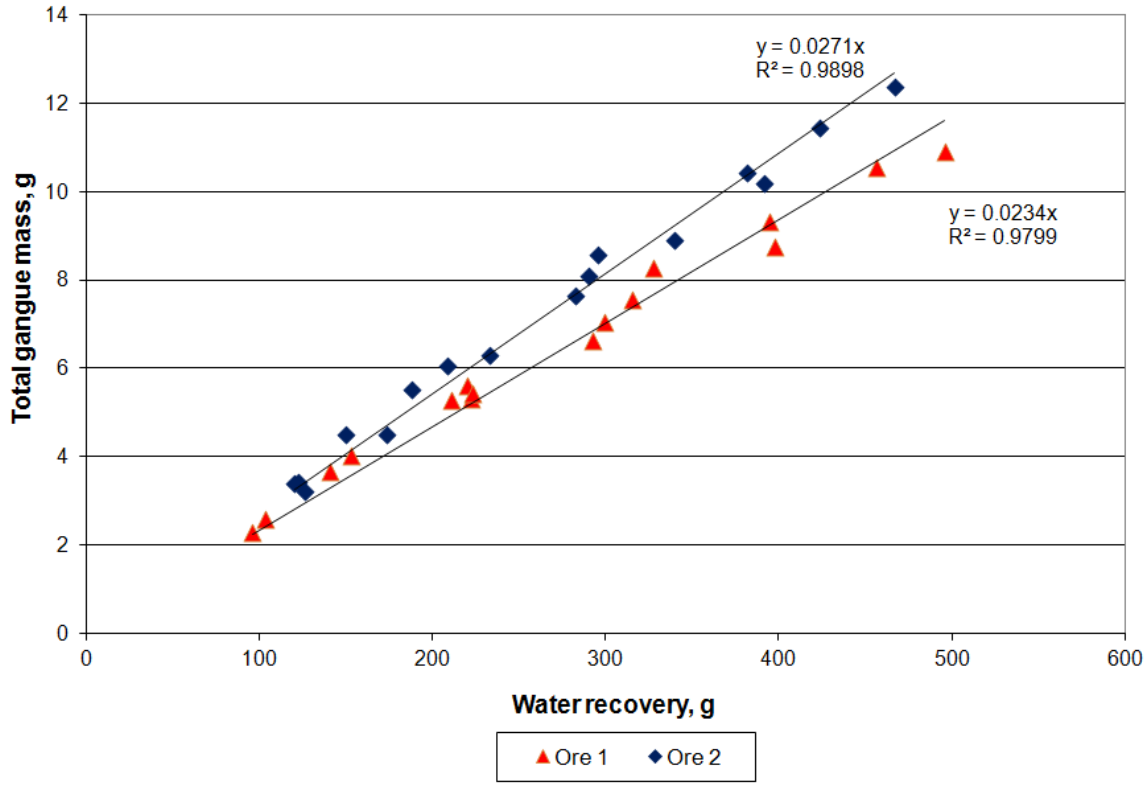

Figure 4.27 Total gangue versus water recovered in all the tests conducted on Merensky ore #1 and #2 using Dow 200 in its pure form and in blends with MIBC, at a total frother dosage of 50 g/t
(SIBX collector = 150 g/t, Stypres 504 (guar) depressant = 500 g/t)

An important point is that the degree of entrainment, for both ores, is independent of the frother type, i.e. of whether the pure frother or the frother blend was being used. For each ore, all the data points fit a straight line passing through the origin with R^2 values of 0.98 or more. This is as noted previously by Rahal et al (2001) and Wiese and Harris (2012). Thus, depending on the water recovery in each flotation test, between 2 g and 12 g of solids will be recovered by entrainment (as water recovery increases from 100 g to 500 g). The fact that the grades of copper, nickel and sulphur improve when using 4:1 blends of Dow 200/Dow 250 with MIBC

suggests that irrespective of additional water recovery and consequent additional solids recovery by entrainment, more values are being recovered when using the blends than the pure frothers.

4.5 Bubble size Measurements

The three alcohol type frothers and the two polyglycol type frothers that were used in the batch flotation experiments were used in another series of experiments to determine bubble sizes. Two phase experiments were conducted by incrementally adding the alcohols to Dow 200 or Dow 250 and performing bubble size measurements as described in section 3.6. The bubble size distributions are plotted in the appendix B. Figure 4.31 shows the bubble sizes measured in the presence of pure alcohols and in blends with 2 ppm of Dow 200 frother at total concentration ranging from 0 to 30 ppm. For the blends, the bubble size at zero represents 0 ppm frother and the bubble size at 5 represents 2 ppm Dow 200 with 3 ppm alcohol. The alcohol concentration was increased while that of the Dow 200 remained constant. As expected the results indicate that the mean bubble diameter decreases roughly exponentially with increasing dosage of pure alcohol to a minimum point beyond which no further reduction in bubble size is observed (see section 2.5.2). Results from the blends follow a similar pattern to those produced by the pure frothers. In comparison to pure frothers, the bubble sizes for blends are significantly lower at the concentrations below the critical coalescence concentration of each alcohol. However, above the critical coalescence concentration, the bubble sizes for the blends follow a slightly different pattern from that of the pure frothers. The difference observed was small but was observed for all the frothers used in the study.

Figure 4.32 shows the results of a similar set of experiment conducted with the different alcohols in their pure forms as well as in blends with Dow 250. The mean bubble diameter follow a similar pattern to that obtained when using Dow 200 but with a higher reduction in size compared to that obtained with Dow 200. The smaller bubble size could well explain the improved recoveries obtained using blends of Dow 250 frother.

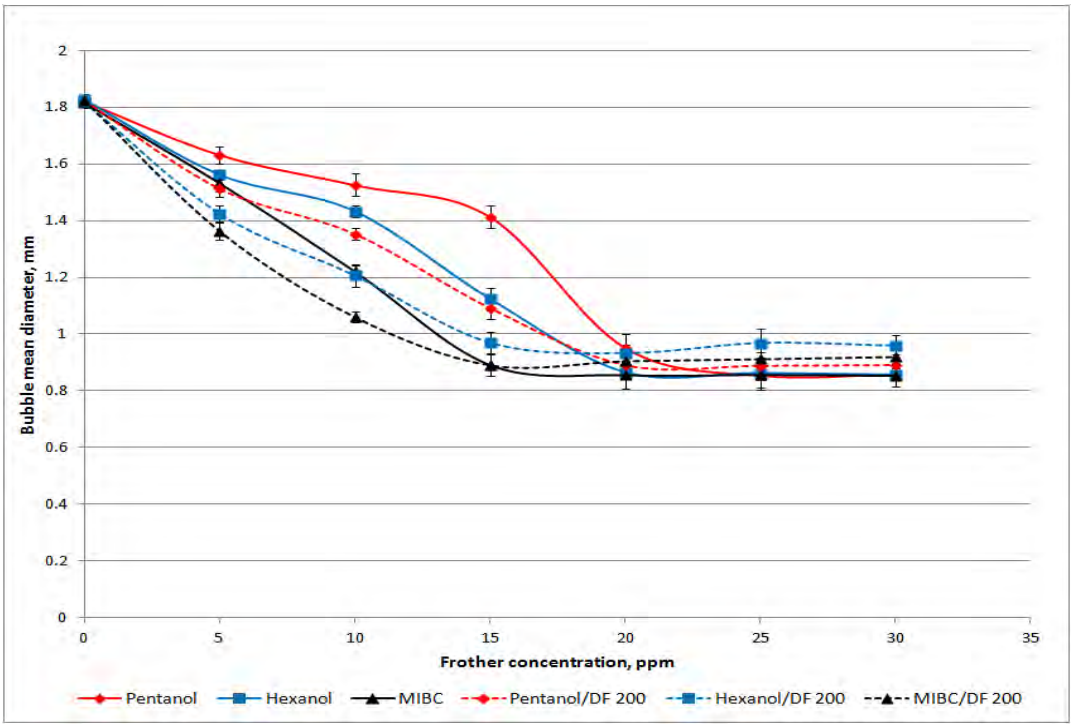

Figure 4.31 Bubble sizes for the three alcohol frothers in their pure forms and with the addition of 2 ppm Dow 200

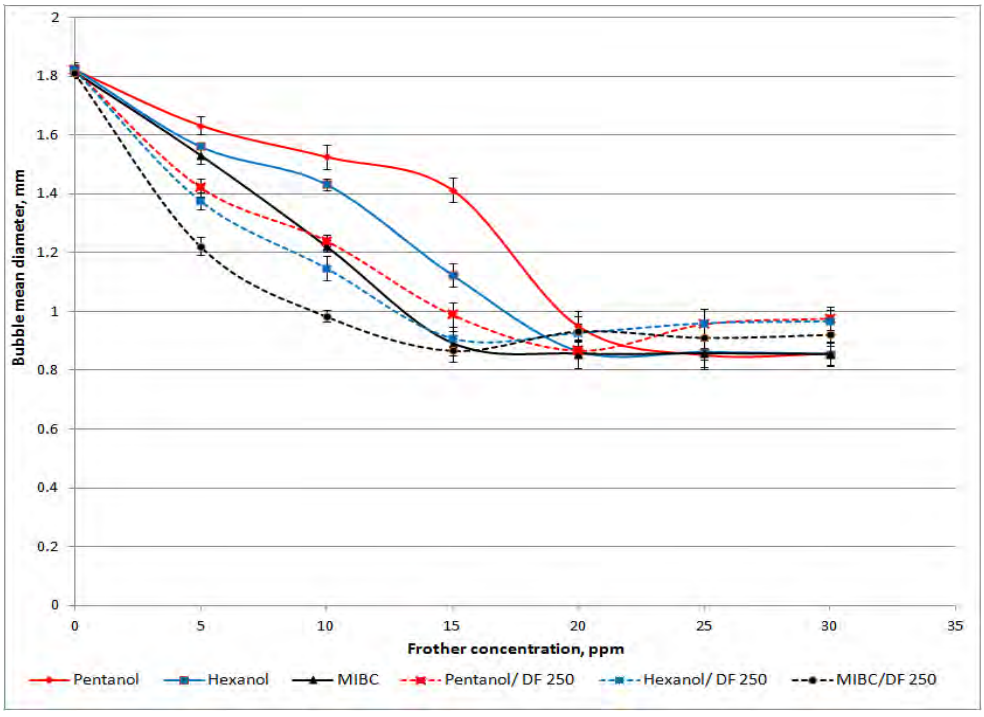

Figure 4.32 Bubble sizes for the three alcohol frothers in their pure forms and with the addition of 2 ppm Dow 250

Figure 4.33 plots the results obtained when Dow 200 and Dow 250 were added to 1-pentanol. For 1-pentanol alone, the trend follows roughly exponential decay curve to a minimum point beyond which no further decrease in bubble size was observed. For the blends significant bubble size reduction was observed below the critical coalescence concentration of 1-pentanol with higher reduction in bubble size being achieved from blends of Dow 250 with pentanol than from the equivalent tests using Dow 200. The critical coalescence concentration, the bubble sizes being slightly larger than that obtained using pure pentanol.

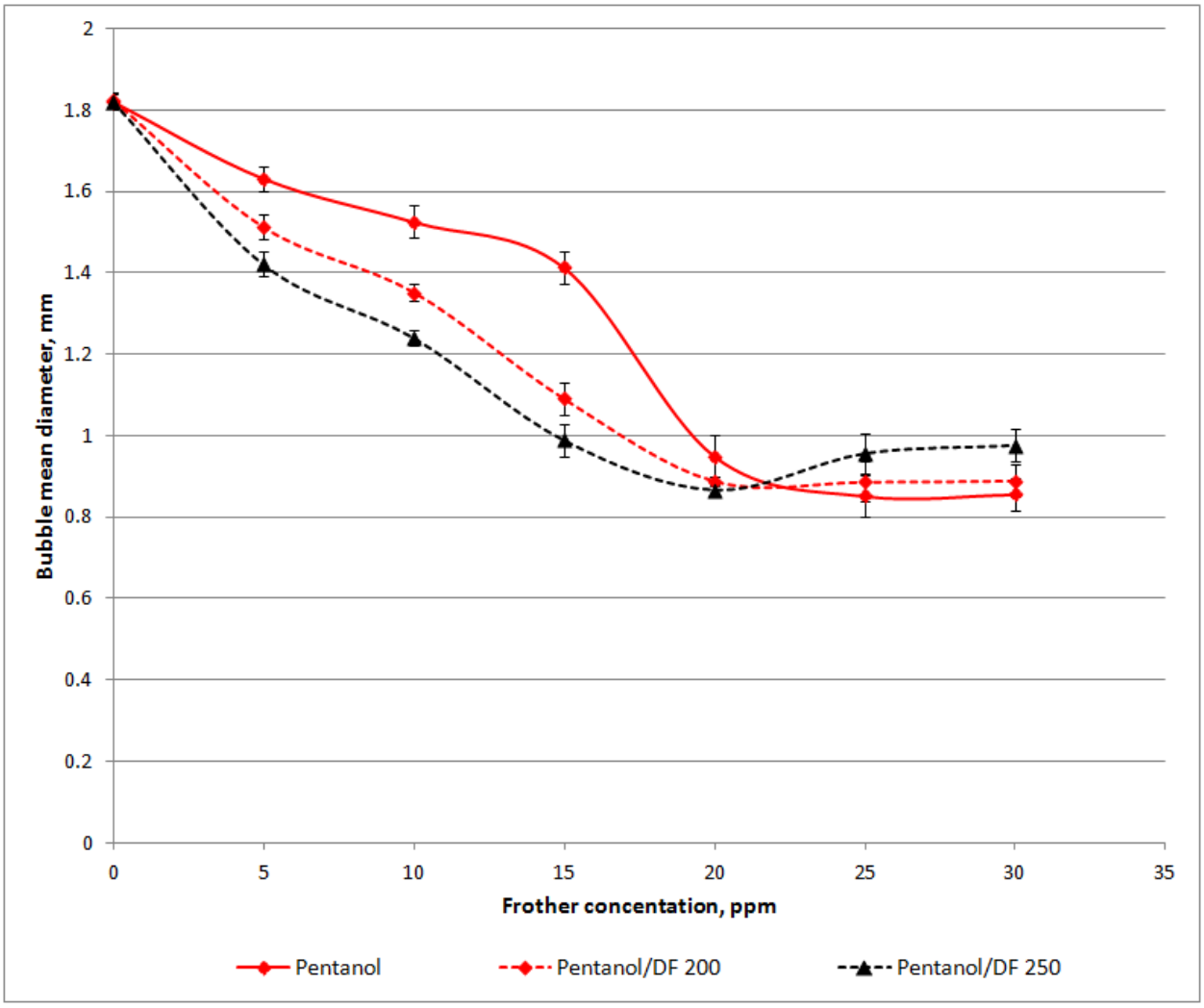

Figure 4.33 Bubble sizes obtained for the additional of 2 ppm Dow 200 and Dow 250 to 1-pentanol

Figures 4.34 and 4.35 show similar plots of the effect on bubble size of Dow 200 and Dow 250 addition to 1-hexanol and MIBC. The smallest bubble sizes were obtained with blends of Dow 250 and MIBC, which also produced the highest recoveries reported earlier in this chapter.

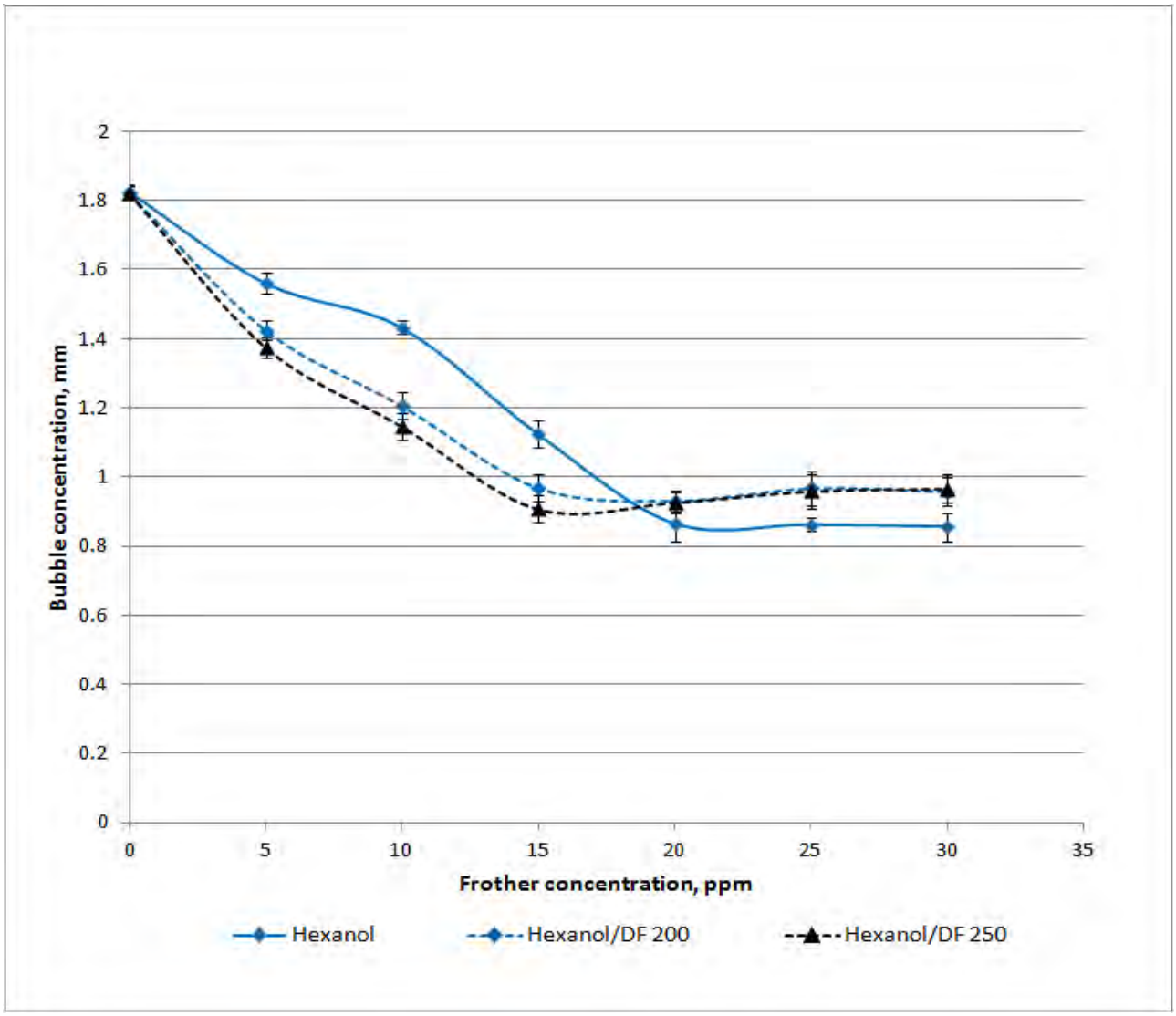

Figure 4.34 Bubble sizes obtained for the additional of 2 ppm Dow 200 and Dow 250 to 1-hexanol

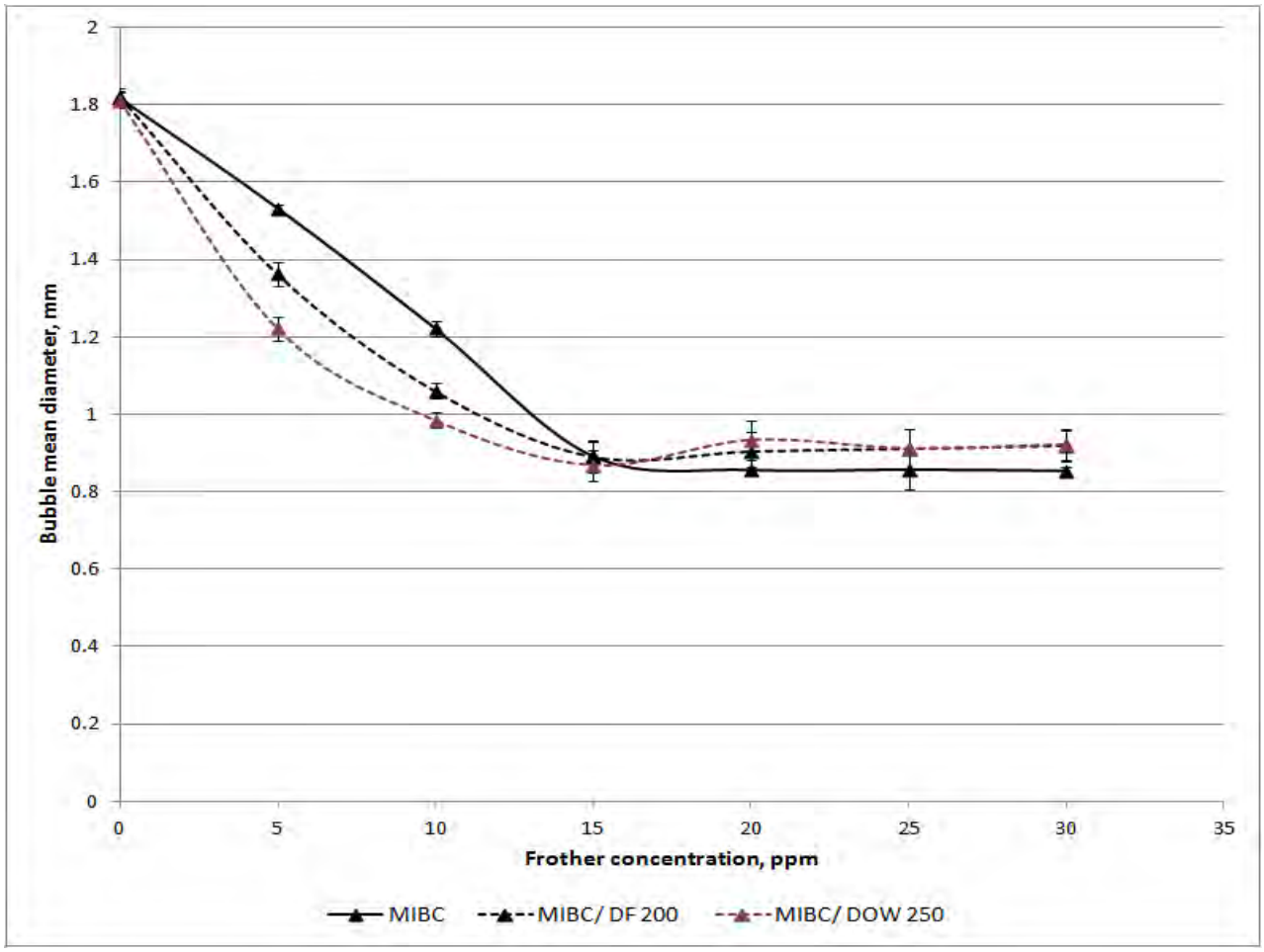

Figure 4.35 Bubble sizes obtained for the additional of 2 ppm Dow 200 and Dow 250 to MIBC

CHAPTER FIVE
DISCUSSIONS

Experiments were conducted to investigate the effect of frother blends on the flotation of PGM bearing ores. Two ores were selected from the Merensky Reef in the Bushveld Igneous Complex, South Africa. The first phase of experiments involved the use of batch flotation tests, using frothers selected to cover a range of polyglycols and alcohols. Two phase tests were then carried out to measure the bubble sizes. It was found in preliminary work that the addition of only a small amount of one type of frother to the other type led to improved performance in terms of the amount of water and solids recovered. In this phase of experiments, only 1-pentanol representing the alcohol family of frothers and Senfloth 516 representing polyglycol family of frothers, were used.

It is well understood from the literature that an increase in water recovery is related to an increase in froth stability (Melo and Laskowski, 2007). Water recovery can therefore be used as a measure of froth stability in experiments involving different type of frothers, as was used in this study. The mechanism by which frother blends produce more stable froths than pure frothers has not been covered much as limited literature is available (Laskowski et al 2003; Tan et al. 2005; Hernandez-Aguilar et al. 2006; Elmahdy and Finch 2009; and Zhang et al 2012a,b). The current discussion will try to explain the possible mechanism when frother blends are used in flotation.

Frothers are generally hetero-polar molecules with a combination of non-polar (hydrophobic) and polar (hydrophilic) parts. It is this mixed polarity that enables the frother molecule to adsorb at the air-water interface with the hydrophilic group orientated towards the water and the hydrophobic group towards the air. This interrupts the interaction between water molecules and lowers the surface tension (Finch et al., 2008). The surface tension of aqueous surfactant solutions is mainly determined by the groups and molecules present in the outermost layer of the surface. With frother blends, one of the possible mechanisms is that the addition of alcohol to the polyglycol reduces the average interaction between the molecules of water. This would reduce the surface tension of the system. As explained by Samanta and Ghosh (2011), aliphatic alcohols having four or more carbon atoms penetrate the polyglycol micelles forming a mixed micelle

which adsorbs at the air–water interface and competes for position in the surface layer with the polyglycol molecules. The hydrophobic interaction between the hydrocarbons tails of polyglycol is therefore reduced inducing weaker adsorption of the polyglycol molecules.

The blends used in the ratio of 2:3 and 3:2 alcohol /polyglycol also produced slightly higher water and solids recovery than the pure frother at the same dosage but a much higher effect was observed for the blends in the ratio of 1:4 and 4:1. The fact that the addition of small amounts of alcohol resulted in the observed effect may be attributed to the fact that the surface excess concentration of polyglycol decreased with an increase in alcohol concentration, whereas the same for alcohol increased. The total surface excess concentration of polyglycol and alcohol, however, decreased with an increase in alcohol concentration. It is suggested that at a certain composition, a change over occurs in the forces which stabilise the thin film among the alcohol and polyglycols (Samanta and Ghosh, 2011).

The observed effects might also have been caused by the inherent surface activity of the longer alcohols, their preferential adsorption at interfaces and a high inclination toward the formation of mixed micelles. The concentration of a given frother at which certain solution properties change dramatically, indicating formation of frother aggregates or micelles, has been termed in some literature as the critical micelle concentration (CMC) (Myers, 2006).

From the results, it can be speculated that in the frother blend in which alcohol was introduced to the polyglycol, the CMC of the mixture decreased initially when small amount of alcohol was added, it reached a minimum point and thereafter started increasing from that point. This initial decrease in CMC may be attributed to the preferential association of the alcohol with the polyglycol micelle, followed by an increase in the solubility of the polyglycol monomer as the solvent became less aqueous in character. This kind of behaviour has also been observed for aqueous solutions containing non-ionic surfactants and other water-miscible organic solvents (Myers, 2006).

The forces that may be leading to micelle formation in the alcohol/polyglycol blend cannot be explained in the present study with the available data. There is undoubtedly still room for a spectrum of mechanisms to be explored on theoretical and practical grounds in ongoing research into the understanding of the frothers and their blends.

Experiments with blends using the ratio of 1:4 and 4: 1 were extended to include other alcohols and polyglycols. The alcohols included 1-pentanol, 1-hexanol and MIBC; the polyglycols included Dow 200 and Dow 250. It was evident from the results that the amount of both solids and water recovered increased with the trend 1-pentanol < 1-hexanol < MIBC in case of the alcohols. The addition of polyglycol frother to alcohol at a ratio of 1:4 resulted in the same trend, but with higher water and solids recoveries being achieved than when using any of the alcohol frothers individually.

The results showed that the properties of the polyglycol frothers changed with the introduction of small amounts of long-chain alcohols, especially higher than C4[4]. The short chain alcohols have a tendency to remain in solution thereby promoting the formation of expanded water structures around the hydrophobic region of the alcohols molecules (Mukherjee et al., 2011), which may result in increased surface tension of the system. The presence of such short chained alcohols which are infinitely miscible in water will modify the water solvent leading to the formation of less polar medium. According to Li et al. (2009), this factor combined with the adsorption of alcohol at micelle-water interface, will cause a restriction to the micellization of polyglycol molecules which may lead to increased surface tension. The longer chained alcohols on the other had a positive effect on both water and solid recovery when used as blends compared to their pure forms. 1-hexanol produced a greater effect compared to 1-pentanol at the same dosage. MIBC had a greater effect than 1-hexanol, although they both contain the same number of carbons. The higher performance of MIBC over 1-hexanol may be attributable to the presence of a branched methyl group on MIBC. It has been found in many instances that surfactants with branched hydrophobic groups will lower the surface tension of a solution more rapidly than a straight chain molecule of equal carbon number (Rosen, 2004).

It was also seen in the results that slightly higher solids recoveries but significantly higher water recoveries were obtained from tests in which Dow 250 was used rather than Dow 200. This supports the findings of Laskowski et al. (2003) that increasing the number of propoxy groups per molecule, in the homologous series of polyglycol frothers, improves the ability of these compounds to produce a more stable froth. The ability of these compounds to reduce the surface

[4] 1-butanol was also used, but produced no froth at all and was omitted from the results

tension of the system depends on their hydrophobic and hydrophilic parts. Since the hydrophilic parts of the two polyglycols are the same, the main difference in their structure is in the aliphatic hydrocarbon chains, with that of Dow 250 being longer than that of Dow 200. In the same homologous series, increases in the length of the hydrocarbon chain usually results in an increase in hydrophobicity.

It is often observed that the amount of froth produced by the members of a homologous series of a frother will go through a maximum as the chain length of the hydrophobic group increases. This is probably due to the conflicting effects of the structural changes. In one case, a longer-chain hydrophobe will result in a lower CMC and a more rapid lowering of surface tension. However, if the chain length grows too long, low solubility and slow diffusion may become a problem (Rosen, 2004). It could be that the number of moles of frother added decreases as the molecular weight increases i.e. less moles of frother are added as the molecular weight increases. It seems that the effect of the polyglycol as an additive in the blend has a correlation with the relative amount of the added material that is located in the interfacial film. The higher the mole fraction of the material added that is adsorbed at the interface, the more stable is the resulting froth and consequently the water recovered.

Analysis of the flotation performance was carried out by measuring the amount of valuable minerals reporting to the concentrate. Feeds, concentrates and tails were filtered, dried, weighed and analysed for copper, nickel and sulphur. Analysis of these sulphide minerals recovered in the concentrate is assumed to give an indication of PGM recovery due to the strong association between the sulphides and the PGMs in the Merensky reef. The results have indicated that blends produced higher recoveries for both copper and nickel than pure frothers. These higher recoveries in most instances were accompanied with higher grades. This may be attributed to the increase in solids holding capacity of the bubbles formed as a result of using the frother blend.

The mechanism by which frother blends produce both improved recovery and grades is a point that still requires investigation. Literature is sparse in the topic. It may be argued that the use of frother blends result in independent control of the most important characteristic in flotation; providing optimum hydrodynamic properties in the pulp and optimum properties of the froth (Finch et al., 2006). This will mean independent control of bubble size and froth stability. In the study by Zhang et al. (2012b), it was shown that it is actually possible for the frother blend to

have independent control over the froth properties, namely water overflow rate, which is the measure of stability, and the two pulp hydrodynamic properties, Sauter mean bubble diameter and gas hold up. In their study in which alcohol was used as base frother with tetraethylene glycol as an additive, Zhang et al. (2012b) found that water flow rate increased with increase in tetraethylene glycol with Sauter mean diameter independent of the tetraethylene glycol concentration. The mechanism behind this was said to be froth partitioning. Alcohol partitioning to the froth was much less thus allowing enough alcohol concentration above CCC to remain in the solution which is sufficient to maintain bubble size.

It is also to be expected that the effects of a frother on the air water interface can be time dependant, because of the significant differences in the rates of adsorption of the different species at the interface and, in some cases, the time required for specific frother adsorption mechanism to take place. In frothers with a range of molecular weight, as in the case of alcohols and polyglycols, the smaller chains will routinely adsorb first, but they also desorb more readily and are, over time, replaced by the higher-molecular-weight chains (Myers, 2006).

As shown from the beginning, that the presence of small amounts of one frother in a blend can have a dramatic effect on the flotation performance. An example of such an effect is the increased water and solids recovery as well as the improved valuable mineral recovery and grade. To be able to explain the mechanism for increased mineral recovery as well as grade, we can turn to the two fold explanation as given by Myers (2006). Firstly, because of its less hydrophilic head group (the hydroxyl), the alcohol will be more efficiently adsorbed at the surface; and second because of the smaller size of the head group, the alcohol can be packed into the adsorbed layer between adjacent molecules of the polyglycol frother, resulting in a greater surface excess and a lower surface tension. It is this kind of close packing of alcohol molecules into the polyglycol molecules at the air bubble interface that may be leading to increased bubble holding capacity and thus improved valuable mineral recovery and grade. This close packing together with independent control of bubble size and froth stability as explained by Zhang et al. (2012) can help to explain the improved flotation performance when frother blends are used as compared to single frothers. Once the primary frother concentration has reached its CMC, the less soluble frother can be solubilised into micelles so that the surface tension will be determined more directly by the primary surfactant species. This may also help to explain why frother blends

in the ratio of 2:3 and 3:2 could not produce as improved performance as when smaller amounts of frother was added to another.

Batch flotation experiments were also conducted using a second ore from the Merensky reef. The tests were conducted under the optimum conditions, i.e. with polyglycol/alcohol frothers at the ratio of 4:1 which gave the best results from the previous experiments. The results exhibit the same trends as results from the experiments with ore #1. Higher amounts of water were recovered from tests using Merensky ore #2 than from tests using Merensky ore #1. This may be due to differences in the mineralogy of the gangue minerals in the two ores resulting in differences in the mechanism of froth stabilisation. The differences in the amounts of entrained solids due to differences in particle size may also play a part.

Copper and nickel recoveries from Merensky ore #2 were lower than those obtained from Merensky ore #1. This is likely due to the fact that the base metal sulphide content of ore #2 was lower than that of ore #1. The entrainability values determined for the two ores relate to a fixed amount of solids entrained per unit water recovery. This means that the lower the amount of water recovery, the lower the entrained solids. It is clear from the results that the entrainment was higher for Merensky ore # 2 than Merensky ore # 1.

Another batch of experiments was conducted to measure the effect of frother blends on the mean bubble size in two phase system. Tests were conducted by incrementally adding frother and performing bubble size measurements. The two polyglycol frothers Dow 250 and Dow 200 were used as base frother at constant dosage of 2 ppm. Three alcohol frothers, 1-pentanol, 1-hexanol and MIBC were used as additive up to a total dosage ranging from 2 to 30 ppm. Results for all frothers showed that mean bubble diameter decreased roughly exponentially with increased dosage of pure alcohol frother to a minimum point beyond which no further reduction in bubble sizes was observed. This concentration is what is termed the critical coalescence concentration (CCC) (Laskowski, 2003). In the blends, the curves followed a similar pattern as that produced by the pure frothers. The bubble size for blends was reduced significantly at the concentration below the critical coalescence concentration of each alcohol as compared to pure frothers. However above the critical coalescence concentration the bubble sizes for the blends followed a different pattern from that of the pure frothers. This difference was observed for all the frothers used in the study.

To explain the increase in bubble size for the blends at higher concentration, we can go back to the concept of mixed micelles. Each mixed micelle contains several hydrophobes either from a chain or from different chains. At low frother concentrations, nearly all frother molecules are associated with the polyglycol in the formation of mixed micelles. At high frother concentration, such binding reaches a saturation point, beyond which free micelles are expected to coexist with the mixed micelles (Mukherjee et al., 2011). At higher frother concentration the free micelles greatly outnumber the mixed micelles, almost approaching the value of the pure surfactant solution at the same concentration. At this stage only the primary frother is involved in the reaction. The mechanism can be same as the frother partitioning as noted by Zhang et al. (2012).

CHAPTER SIX
CONCLUSIONS

This chapter puts together the key findings of the study. The main objective of the study was to investigate the behaviour of frother blends in the flotation of platinum bearing ores. The two ores were selected from the Merensky Reef in the Bushveld Igneous Complex, South Africa. The first phase of experiments involved the use of batch flotation tests, using the frothers selected to cover a range of polyglycols and alcohols. The conclusions are presented as answers to the key questions that were investigated

Effect of different blends of low molecular weight alcohol and polyglycol frothers on solids and water recovery in PGM flotation compared to using the frothers on their own

The use of frother blends improved performance in terms of the amount of water and solid recovered as compared to using frothers on their own. The addition of only a small amount of one frother to the other led to improved performance as compared to single frother. Experiments with the alcohol/polyglycol blends in the ratio of 1:4 and 4: 1 produced higher results compared to other blend ratios studied. The alcohols included 1-pentanol, 1-hexanol and MIBC and the polyglycols included Senfroth 516, Dow 200 and Dow 250. The amount of both solids and water recovered increased with the trend 1-pentanol < 1-hexanol < MIBC in case of the alcohols. Slightly higher solids recoveries but significantly higher water recoveries were obtained from tests in which Dow 250 was used rather than Dow 200. The trend was the same for both ores used. Higher amounts of water were recovered from tests using Merensky ore #2 than from tests using Merensky ore #1, probably due to differences in the mineralogy of the gangue minerals in the two ores resulting in differences in the mechanism of froth stabilisation.

It may be concluded that the frothing properties of a polyglycol frother change with the introduction of small amounts of long-chain alcohols.

Effect of different blends of low molecular weight alcohol and polyglycol frothers on the concentrate grade and recovery of valuable minerals in PGM flotation compared to using the frothers on their own

Analysis of the flotation performance was carried out by measuring the amount of valuable minerals reporting to the concentrate. The results indicated that blends produced higher recoveries for copper, nickel and sulphur than frothers on their own. These high recoveries in most instances were accompanied by high grades. This was attributed to the increase in solids holding capacity of the small bubbles formed as a result of using the frother blends. Copper and nickel recoveries from Merensky ore #2 were lower than those obtained from Merensky ore #1 possibly due to the fact that that the base metal sulphide content of ore #2 was lower than that of ore #1.

Effect of different blends of low molecular weight alcohol and polyglycol frothers on bubble size reduction and bubble size distribution compared to using the frothers on their own

Experiments were conducted in two phase systems to measure the effect of frother blends on the bubble size produced. Results for all frothers showed that mean bubble diameter for pure frothers decreased roughly exponentially to a minimum beyond which no further reduction in bubble sizes was observed. In the blends, the curves followed a similar pattern but the bubble size for blends was reduced significantly at concentrations below the critical coalescence concentration of each alcohol. Above the critical coalescence concentration the bubble size for the blends was observed to follow a different pattern from that of the pure frothers where by bubble sizes increased.

Overall the conclusions from this investigation suggest that frother blends may help improve the performance of a circuit by control of bubble size, independently control of froth stability and solids holding capacity. A synergistic effect was observed, with the use of the frother blends resulting in enhanced performance compared to any of the frothers used individually. Higher water and solids recoveries were obtained from tests using frother blends than from tests using the pure frothers. The highest valuable mineral recoveries were achieved with the use of certain frother blends (1:4, 4:1). It has therefore been shown that there is scope for plants to implement the use of a dual frother system in order to improve the performance of the circuit and that the

addition of just a small amount of one type of frother to another is needed to bring about these enhancements.

CHAPTER SEVEN
RECOMMENDATIONS

The results obtained from this study suggest that frother blends may be used to improve the performance of a flotation circuit. The use of mixed frother systems may therefore be considered as a method for obtaining the optimal performance for practical frother application. The investigation has opened the way for extensive research on blending frothers. The ability of the frother blend to produce both improved recovery and grades on two Merensky ores as compared to the single frother has been indicated. Research is still required to determine the mechanism/s involved.

The research on frother blends can also investigate the effect of blending alcohols and polyglycols at specific molecular weight. It is expected that the effects of a frother at the air water interface can be time dependant. This is mainly due to the significant differences in the rates of adsorption of the different species at the interface and, in some cases, the time required for specific frother adsorption mechanism to take place. In frothers with a range of molecular weight (as it is in the case of alcohols and polyglycols), the smaller chains will routinely adsorb first, but they also desorb more readily and are, over time, replaced by the higher-molecular-weight chains. It is therefore important to look at the performance of the blends at different molar ratios.

The research can also focus on which particle sizes are affected. A recovery by size investigation can help in understanding the mechanism involved.

The force that may be leading to micelle formation in the alcohol/polyglycol blend has not been fully explained in the present study with the available data. There is therefore still room for research in this area.

The use of polyglycol or alcohol frothers is common in most mineral industries. Understanding the effects that the blends can have is important in both academic and industrial spheres. Since frother blends have shown a positive effect on water, solids and valuable mineral recovery compared to their pure forms, it is important that the research is expanded to include analysis of the PGMs. Further testwork may be undertaken to quantify the results in a rougher, cleaner, re-

cleaner programme and possibly on a continuous pilot plant scale. Bubble size measurements can also include the three phase system. The research should also focus on the use of the available machine vision measurements to monitor the change in froth stability and bubble solids loading capacity in the froth phase. More ores can also be included in the investigation to include rare earth metals.

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APPENDICES

APPENDIX A

Batch flotation Data

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
A1	SENF 516	C1	2	5.32	44.13	5.32	44.13	8.31	46.28	11.23	27.32	26.10	33.59
	50 g/t	C2	6	5.52	89.05	10.84	133.18	6.32	71.75	11.17	55.39	22.94	60.16
	ORE # 1	C3	12	3.62	89.71	14.46	222.89	5.18	78.50	9.52	62.96	20.10	70.31
		C4	20	4.92	132.91	19.38	355.80	4.02	81.51	7.57	67.07	16.38	76.79
		FEED		1008.81				0.07		0.18		0.26	
		TAILS		978.22				0.02		0.07		0.10	
A2	SENF 516	C1	2	4.34	73.11	4.34	73.11	7.12	55.03	10.60	26.07	20.70	33.36
	50 g/t	C2	6	4.32	59.42	8.66	132.53	4.59	70.88	8.49	41.67	15.91	51.16
	ORE # 1	C3	12	4.6	76.94	13.26	209.47	3.25	76.78	6.34	47.63	12.24	60.26
		C4	20	3.98	115.08	17.24	324.55	2.59	79.62	5.17	50.54	10.24	65.55
		FEED		1012.93				0.08		0.17		0.28	
		TAILS		977.58				0.01		0.09		0.09	
A3	SENF 516	C1	2	9.43	114.17	9.43	114.17	6.94	75.01	10.53	43.51	21.90	52.08
	40 g/t	C2	6	5.49	96.74	14.92	210.91	4.90	83.82	8.57	56.06	17.45	65.64
	PENT	C3	12	4.77	127.98	19.69	338.89	3.84	86.66	7.06	60.90	14.49	71.92
	10 g/t	C4	20	3.57	86.49	23.26	425.38	3.30	87.87	6.11	62.31	12.80	75.06
	ORE # 1	FEED		1025.23				0.07		0.18		0.29	
		TAILS		989.86				0.01		0.09		0.10	
A4	SENF 516	C1	2	9.21	104.79	9.21	104.79	5.64	71.34	11.86	47.85	21.70	52.81
	40 g/t	C2	6	5.53	108.78	14.74	213.57	4.09	82.69	9.22	59.57	17.07	66.49
	PENT	C3	12	4.31	134.1	19.05	347.67	3.27	85.41	7.54	62.90	14.23	71.62
	10 g/t	C4	20	3.02	76.44	22.07	424.11	2.85	86.38	6.60	63.78	12.66	73.82
	ORE # 1	FEED		1019.83				0.07		0.19		0.28	
		TAILS		987.2				0.01		0.50		0.10	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
A5	SENF 516	C1	2	6.85	98.19	6.85	98.19	7.30	70.96	11.20	36.16	22.20	44.99
	30 g/t	C2	6	3.72	92.62	10.57	190.81	5.35	80.22	10.35	51.58	18.86	58.97
	PENTANOL	C3	12	3.08	76.45	13.65	267.26	4.30	83.26	8.74	56.26	16.56	66.90
	20 g/t	C4	20	4.33	112.95	17.98	380.21	3.35	85.38	7.00	59.36	13.70	72.87
	ORE # 1	FEED		1011.01				0.08		0.18		0.28	
		TAILS		980.88				0.01		0.09		0.09	
A6	SENF 516	C1	2	6.78	95.52	6.78	95.52	6.03	66.12	11.41	39.44	20.90	42.29
	30 g/t	C2	6	3.33	100.46	10.11	195.98	4.54	74.26	9.47	48.80	17.44	52.62
	PENTANOL	C3	12	3.94	86.91	14.05	282.89	3.51	79.75	7.65	54.76	14.75	61.83
	20 g/t	C4	20	4.67	120.71	18.72	403.60	2.75	83.06	6.08	58.03	12.46	69.62
	ORE # 1	FEED		1021.37				0.08		0.18		0.28	
		TAILS		988.54				0.01		0.08		0.10	
A7	SENF 516	C1	2	7.91	112.21	7.91	112.21	6.09	67.00	9.48	32.88	20.10	42.56
	20 g/t	C2	6	4.56	91.5	12.47	203.71	4.47	77.57	8.84	48.33	17.06	56.96
	PENTANOL	C3	12	3.63	81	16.10	284.71	3.62	81.06	7.68	54.21	15.27	65.79
	30 g/t	C4	20	2.38	72.97	18.48	357.68	3.20	82.20	6.91	55.98	14.06	69.57
	ORE # 1	FEED		1020.05				0.08		0.19		0.29	
		TAILS		984.42				0.01		0.10		0.12	
A8	SENF 516	C1	2	7.92	115.98	7.92	115.98	7.77	73.15	11.03	38.92	25.10	50.71
	20 g/t	C2	6	4.88	82.37	12.80	198.35	5.48	83.49	9.83	56.04	20.03	65.40
	PENTANOL	C3	12	2.91	85.69	15.71	284.04	4.60	86.01	8.58	60.05	17.86	71.57
	30 g/t	C4	20	2.42	79.89	18.13	363.93	4.04	87.03	7.62	61.58	16.10	74.48
	ORE # 1	FEED		1020.71				0.08		0.18		0.28	
		TAILS		991.44				0.01		0.09		0.10	

Run No.	Frother Type and Dosage	Sampe ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
A9	SENF 516	C1	2	9.67	115.16	9.67	115.16	7.39	73.88	9.95	37.81	20.60	46.67
	10 g/t	C2	6	5.28	112.51	14.95	227.67	5.45	84.19	9.53	56.01	17.95	62.87
	PENTANOL	C3	12	3.36	106.12	18.31	333.79	4.57	86.56	8.69	62.58	16.58	71.14
	40 g/t	C4	20	2.93	98.1	21.24	431.89	4.00	87.70	7.82	65.29	15.25	75.86
	ORE # 1	FEED		1021.70				0.07		0.18		0.54	
		TAILS		987.48				0.01		0.09		0.10	
A10	SENF 516	C1	2	9.49	114.7	9.49	114.70	6.43	73.75	9.80	43.53	21.10	56.58
	10 g/t	C2	6	5.29	96.76	14.78	211.46	4.51	80.56	7.75	53.57	16.28	67.98
	PENTANOL	C3	12	3.96	98.66	18.74	310.12	3.67	83.08	6.37	55.87	13.68	72.41
	40 g/t	C4	20	2.86	96.25	21.60	406.37	3.21	83.93	5.61	56.72	12.18	74.34
	ORE # 1	FEED		1016.14				0.06		0.16		0.31	
		TAILS		980.59				0.01		0.09		0.09	
A11	PENTANOL	C1	2	4.17	89.32	4.17	89.32	8.23	58.58	9.93	20.59	27.90	33.75
	50 g/t	C2	6	2.79	51.74	6.96	141.06	6.04	71.76	10.67	36.91	24.41	49.29
	ORE # 1	C3	12	2.07	25.97	9.03	167.03	4.87	75.13	10.50	47.13	21.75	56.98
		C4	20	2.63	30.39	11.66	197.42	3.90	77.63	9.15	53.04	18.95	64.11
		FEED		1005.83				0.07		0.20		0.31	
		TAILS		978.06				0.01		0.10		0.13	
A12	PENTANOL	C1	2	4.44	82.44	4.44	82.44	8.07	65.54	10.15	24.78	26.10	34.00
	50 g/t	C2	6	2.48	65.92	6.92	148.36	5.72	72.45	10.11	38.47	23.55	47.81
	ORE # 1	C3	12	3.86	28.78	10.78	177.14	3.89	76.70	8.17	48.42	19.63	62.08
		C4	20	2.3	40.08	13.08	217.22	3.28	78.40	7.19	51.70	17.82	68.36
		FEED		1005.28				0.07		0.18		0.35	
		TAILS		976.01				0.01		0.09		0.11	

Run No	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
B1	DOW 250	C1	2	7.9	122.88	7.9	122.88	5.42	64.89	9.55	36.9	21.57	49.61
	10 g/t	C2	6	6.07	98.11	13.97	220.99	3.64	77.05	7.30	49.91	15.85	64.46
	PENTANOL	C3	12	4.01	78.01	17.98	299	2.96	80.64	6.19	54.43	13.54	70.88
	40 g/t	C4	20	3.11	98.04	21.09	397.04	2.56	82.01	5.45	56.29	12.08	74.2
	ORE # 1	FEED		1007.36				0.08		0.19		0.28	
		TAILS		972.27				0.01		0.09		0.09	
B2	DOW 250	C1	2	7.83	116.16	7.83	116.16	6.03	65.02	9.00	32.02	17.01	35.88
	10 g/t	C2	6	6.11	106.58	13.94	222.74	4.05	77.61	7.64	48.38	13.98	52.51
	PENTANOL	C3	12	4.56	69.7	18.5	292.44	3.23	82.26	6.59	55.36	12.59	62.74
	40 g/t	C4	20	3.76	88.25	22.26	380.69	2.74	84.04	5.75	58.14	11.25	67.46
	ORE # 1	FEED		1003.37				0.07		0.20		0.24	
		TAILS		966.15				0.01		0.10		0.13	
B3	DOW 250	C1	2	8.31	131.85	8.31	131.85	5.75	68.49	8.25	31.32	16.60	40.03
	10 g/t	C2	6	4.82	109.1	13.13	240.95	4.14	77.95	8.00	47.94	14.21	54.16
	HEXANOL	C3	12	4.18	121.91	17.31	362.86	3.27	81.15	6.86	54.22	12.59	63.22
	40 g/t	C4	20	4.13	114.78	21.44	477.64	2.69	82.77	5.82	56.98	10.98	68.33
	ORE # 1	FEED		1006.58				0.07		0.17		0.31	
		TAILS		970.03				0.01		0.10		0.11	
B4	DOW 250	C1	2	8.65	130.15	8.65	130.15	7.36	71.57	8.60	33.96	22.50	42.46
	10 g/t	C2	6	6.27	114.99	14.92	245.14	4.91	82.26	8.16	55.57	17.50	56.96
	HEXANOL	C3	12	4.97	118.39	19.89	363.53	3.84	85.87	7.13	64.79	15.46	67.07
	40 g/t	C4	20	4.17	116.73	24.06	480.26	3.24	87.61	6.23	68.48	13.76	72.23
	ORE # 1	FEED		1010.69				0.08		0.21		0.31	
		TAILS		971.66				0.01		0.11		0.13	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
B5	DOW 250	C1	2	8.67	124.66	8.67	124.66	5.59	69.91	10.10	35.71	21.11	50.13
	10 g/t	C2	6	5.15	103.89	13.82	228.55	3.91	78.02	9.19	51.81	17.02	64.43
	MIBC	C3	12	4.28	126.19	18.1	354.74	3.11	81.15	8.06	59.5	14.25	70.63
	40 g/t	C4	20	5.79	120.69	23.89	475.43	2.41	83.15	6.39	62.29	11.61	75.98
	ORE # 1	FEED		1012.05				0.08		0.20		0.31	
		TAILS		973				0.01		0.10		0.09	
B6	DOW 250	C1	2	8.34	132.76	8.34	132.76	5.56	69.09	10.02	36.8	22.80	50.4
	10 g/t	C2	6	5.42	115.34	13.76	248.1	3.83	78.55	8.45	51.23	17.80	64.91
	MIBC	C3	12	3.72	127.65	17.48	375.75	3.12	81.19	7.54	58.03	15.04	69.69
	40 g/t	C4	20	4.18	128.41	21.66	504.16	2.56	82.5	6.28	59.89	12.67	72.73
	ORE # 1	FEED		1006.57				0.07		0.18		0.31	
		TAILS		970.8				0.01		0.09		0.11	
B7	DOW 200	C1	2	7.98	91.62	7.98	91.62	5.84	68.87	10.91	40.81	20.30	46.76
	10 g/t	C2	6	5.64	97.6	13.62	189.22	3.94	79.32	8.36	53.36	15.70	61.72
	PENTANOL	C3	12	3.3	77.12	16.92	266.34	3.27	81.72	7.14	56.63	14.44	70.51
	40 g/t	C4	20	3.96	69.99	20.88	336.33	2.70	83.22	5.95	58.19	12.45	75.01
	ORE # 1	FEED		1009.00				0.08		0.19		0.30	
		TAILS		974.45				0.01		0.09		0.09	
B8	DOW 200	C1	2	7.29	92.32	7.29	92.32	5.99	67.88	10.62	36.46	20.20	42.4
	10 g/t	C2	6	5.26	107.62	12.55	199.94	4.00	77.89	8.55	50.5	15.63	56.49
	PENTANOL	C3	12	3.78	98.32	16.33	298.26	3.18	80.69	7.24	55.63	14.26	67.07
	40 g/t	C4	20	3.96	67.39	20.29	365.65	2.61	82.19	6.08	58.1	12.52	73.14
	ORE # 1	FEED		1008.03	77.12			0.09		0.21		0.32	
		TAILS		975.65				0.01		0.09		0.10	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
B9	DOW 200	C1	2	8.67	122.88	8.67	122.88	6.75	73.51	9.13	36.68	20.00	47.75
	10 g/t	C2	6	5.19	109.57	13.86	232.45	4.73	82.36	8.30	53.32	15.17	57.91
	HEXANOL	C3	12	3.76	100.48	17.62	332.93	3.84	84.93	7.22	58.98	13.83	67.12
	40 g/t	C4	20	3.29	99.14	20.91	432.07	3.28	86.13	6.33	61.39	12.60	72.52
	ORE # 1	FEED		1007.91				0.08		0.19		0.32	
		TAILS		973.13				0.01		0.09		0.10	
B10	DOW 200	C1	2	8.36	118.05	8.36	118.05	5.79	71.68	11.62	30.12	20.60	49.79
	10 g/t	C2	6	5.1	101.5	13.46	219.55	4.02	80.14	10.56	44.07	16.28	63.35
	HEXANOL	C3	12	3.19	119.88	16.65	339.43	3.33	82.18	9.87	50.94	14.09	67.85
	40 g/t	C4	20	4.76	106.86	21.41	446.29	2.64	83.64	7.83	52.02	11.66	72.2
	ORE # 1	FEED		1008.69				0.08		0.10		0.32	
		TAILS		973.27				0.01		0.16		0.10	
B11	DOW 200	C1	2	8.57	129.09	8.57	129.09	5.23	70.01	9.29	38.44	18.30	44.38
	10 g/t	C2	6	4.13	100.05	12.7	229.14	3.88	77.03	7.71	47.32	16.29	58.55
	MIBC	C3	12	4.81	120	17.51	349.14	2.95	80.82	6.23	52.72	13.44	66.58
	40 g/t	C4	20	4.76	95.56	22.27	444.7	2.37	82.64	5.16	55.5	11.34	71.49
	ORE # 1	FEED		1003.06				0.07		0.07		0.31	
		TAILS		966.27				0.01		0.01		0.10	
B12	DOW 200	C1	2	8.24	126.36	8.24	126.36	7.84	74.23	9.67	34.73	22.60	42.64
	10 g/t	C2	6	4.6	129.88	12.84	256.24	5.58	82.36	7.66	42.85	18.91	55.6
	MIBC	C3	12	4.42	118.7	17.26	374.94	4.28	84.91	6.98	52.52	16.35	64.6
	40 g/t	C4	20	4.24	102.11	21.5	477.05	3.50	86.58	6.44	60.32	14.82	72.94
	ORE # 1	FEED		1004.33				0.07		0.19		0.32	
		TAILS		968.51				0.01		0.09		0.12	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
B13	PENTANOL	C1	2	4.17	89.32	4.17	89.32	8.23	58.58	9.93	20.59	27.90	33.75
	50 g/t	C2	6	2.79	51.74	6.96	141.06	6.04	71.76	10.67	36.91	24.41	49.29
	ORE # 1	C3	12	2.07	25.97	9.03	167.03	4.87	75.13	10.50	47.13	21.75	56.98
		C4	20	2.63	30.39	11.66	197.42	3.90	77.63	9.15	53.04	18.95	64.11
		FEED		1005.83				0.07		0.20		0.31	
		TAILS		978.06				0.01		0.10		0.13	
B14	PENTANOL	C1	2	4.44	82.44	4.44	82.44	8.07	65.54	10.15	24.78	26.10	34.00
	50 g/t	C2	6	2.48	65.92	6.92	148.36	5.72	72.45	10.11	38.47	23.55	47.81
	ORE # 1	C3	12	3.86	28.78	10.78	177.14	3.89	76.70	8.17	48.42	19.63	62.08
		C4	20	2.3	40.08	13.08	217.22	3.28	78.40	7.19	51.70	17.82	68.36
		FEED		1005.28				0.07		0.18		0.35	
		TAILS		976.01				0.01		0.09		0.11	
B15	HEXANOL	C1	2	7.45	79.98	7.45	79.98	6.82	70.16	8.97	33.27	19.76	38
	50 g/t	C2	6	4.41	76.63	11.86	156.61	4.81	78.89	7.21	42.59	16.93	51.83
	ORE # 1	C3	12	3.96	74.83	15.82	231.44	3.79	82.83	6.45	50.84	14.87	60.73
		C4	20	2.88	83.27	18.7	314.71	3.27	84.46	6.06	56.4	13.37	64.53
		FEED		1010.73				0.08		0.17		0.23	
		TAILS		977.92				0.01		0.09		0.14	
B16	HEXANOL	C1	2	7.83	89.23	7.83	89.23	5.62	68.15	9.06	33.97	20.21	42.4
	50 g/t	C2	6	4.32	87.98	12.15	177.21	4.13	77.74	7.71	44.84	17.41	56.68
	ORE # 1	C3	12	2.64	96.51	14.79	273.72	3.52	80.73	7.48	52.97	15.87	62.89
		C4	20	2.87	111.18	17.66	384.9	3.02	82.55	6.87	58.05	14.21	67.22
		FEED		1011.05				0.07		0.17		0.54	
		TAILS		978.74				0.01		0.09		0.13	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
B17	MIBC	C1	2	8.7	99.66	8.7	99.66	4.82	65.46	8.87	35.12	15.10	36.32
	50 g/t	C2	6	5.45	86.02	14.15	185.68	3.51	77.63	7.44	47.91	13.98	54.7
	ORE # 1	C3	12	2.8	92.95	16.95	278.63	3.05	80.87	7.23	55.81	13.44	62.98
		C4	20	2.67	105.19	19.62	383.82	2.69	82.62	6.76	60.33	12.88	69.86
		FEED		1007.09				0.08		0.15		0.31	
		TAILS		973.34				0.01		0.09		0.11	
B18	MIBC	C1	2	9.04	93.94	9.04	93.94	5.84	60.65	8.93	37.31	20.40	43.74
	50 g/t	C2	6	5.41	84.43	14.45	178.37	4.23	70.22	7.73	51.6	17.33	59.39
	ORE # 1	C3	12	2.28	99.9	16.73	278.27	3.72	71.53	7.23	55.86	16.19	64.24
		C4	20	2.68	103.2	19.41	381.47	3.25	72.59	6.50	58.32	14.66	67.47
		FEED		1007.88				0.08		0.20		0.33	
		TAILS		976.31				0.01		0.09		0.14	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
D1	DOW 250	C1	2	14.19	163.06	14.19	163.06	3.30	65.36	5.89	44.22	12.30	54.43
	40 g/t	C2	6	4.97	94.3	19.16	257.36	2.72	72.74	5.21	52.84	10.99	65.66
	PENTANOL	C3	12	2.81	79.88	21.97	337.24	2.45	75.08	4.82	56.05	10.24	70.15
	10 g/t	C4	20	3.29	90.28	25.26	427.52	2.18	76.77	4.38	58.51	9.37	73.82
	ORE # 2	FEED		1004.74				0.05		0.14		0.22	
		TAILS		965.37				0.02		0.08		0.09	
D2	DOW 250	C1	2	13.81	145.83	13.81	145.83	4.23	67.6	5.65	40.65	16.90	55.81
	40 g/t	C2	6	6.1	125.61	19.91	271.44	3.31	76.34	5.12	53.12	14.22	67.7
	PENTANOL	C3	12	2.45	71.67	22.36	343.11	3.02	78.1	4.82	56.15	13.30	71.14
	10 g/t	C4	20	2.9	80.3	25.26	423.41	2.72	79.57	4.46	58.69	12.27	74.13
	ORE # 2	FEED		1009.66				0.06		0.14		0.23	
		TAILS		969.64				0.02		0.08		0.11	
D3	DOW 250	C1	2	16.86	164.6	16.86	164.6	3.71	63.68	5.71	49.9	10.60	53.28
	40 g/t	C2	6	9.36	143.16	26.22	307.76	3.05	81.58	4.77	64.75	9.24	72.26
	HEXANOL	C3	12	2.49	65.03	28.71	372.79	2.83	82.86	4.52	67.18	8.87	75.92
	10 g/t	C4	20	3.22	83.41	31.93	456.2	2.58	83.9	4.19	69.26	8.28	78.84
	ORE # 2	FEED		1013.37				0.06		0.15		0.21	
		TAILS		963.09				0.02		0.09		0.07	
D4	DOW 250	C1	2	16.42	191.59	16.42	191.59	3.74	68.01	5.46	43.43	13.90	53.45
	40 g/t	C2	6	8.67	94.25	25.09	285.84	2.86	79.37	4.79	58.24	11.67	68.55
	HEXANOL	C3	12	2.37	72.32	27.46	358.16	2.67	81.03	4.58	61	11.16	71.77
	10 g/t	C4	20	3.91	118.55	31.37	476.71	2.38	82.62	4.20	63.82	10.26	75.36
	ORE # 2	FEED		1023.00				0.06		0.16		0.21	
		TAILS		975.51				0.02		0.08		0.11	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
D5	DOW 250	C1	2	18.12	191.76	18.12	191.76	4.88	75.35	5.74	45.07	14.40	59.54
	40 g/t	C2	6	6.61	77.27	24.73	269.03	3.89	82	5.43	58.26	12.40	69.99
	MIBC	C3	12	3.94	92.58	28.67	361.61	3.45	84.24	5.04	62.6	11.54	75.52
	10 g/t	C4	20	3.91	120.05	32.58	481.66	3.08	85.61	4.63	65.36	10.66	79.24
	ORE # 2	FEED		1024.28				0.06		0.14		0.23	
		TAILS		975.58				0.02		0.08		0.09	
D6	DOW 250	C1	2	19.5	197.49	19.5	197.49	4.84	76.91	6.99	50.58	14.70	61.78
	40 g/t	C2	6	6.76	96.33	26.26	293.82	3.90	83.56	6.62	64.54	12.83	72.63
	MIBC	C3	12	3.39	68.47	29.65	362.29	3.53	85.32	6.14	67.56	12.09	77.23
	10 g/t	C4	20	3.44	117.78	33.09	480.07	3.20	86.36	5.65	69.45	11.23	80.06
	ORE # 2	FEED		1012.32				0.06		0.15		0.23	
		TAILS		964.09				0.02		0.09		0.10	
D7	DOW 200	C1	2	11.81	151.55	11.81	151.55	3.87	64.47	5.80	37.71	14.50	45.89
	40 g/t	C2	6	6.64	92.13	18.45	243.68	2.85	74.28	5.09	51.63	11.67	57.69
	PENTANOL	C3	12	3.62	93.82	22.07	337.5	2.47	76.82	4.58	55.6	10.53	62.31
	10 g/t	C4	20	4.77	87.52	26.84	425.02	2.08	78.64	3.98	58.76	9.20	66.17
	ORE # 2	FEED		1006.46				0.05		0.14		0.24	
		TAILS		963.77				0.02		0.08		0.13	
D8	DOW 200	C1	2	12.61	94.21	12.61	94.21	5.00	67.27	5.88	36.4	18.10	56.13
	40 g/t	C2	6	6.57	110.83	19.18	205.04	3.85	78.92	5.57	52.52	15.43	72.77
	PENTANOL	C3	12	3.15	86.86	22.33	291.9	3.39	80.83	5.14	56.41	14.09	77.36
	10 g/t	C4	20	3.33	106.68	25.66	398.58	2.99	81.93	4.66	58.77	12.72	80.25
	ORE # 2	FEED		1009.06				0.06		0.15		0.25	
		TAILS		966.96				0.02		0.09		0.08	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
D9	DOW 200	C1	2	12.77	140.51	12.77	140.51	4.62	68.26	7.32	42.91	18.40	56.78
	40 g/t	C2	6	6.52	103.52	19.29	244.03	3.47	77.49	6.19	54.86	14.86	69.26
	HEXANOL	C3	12	4.6	105.8	23.89	349.83	2.91	80.41	5.46	59.93	13.08	75.5
	10 g/t	C4	20	4.7	107.81	28.59	457.64	2.48	81.99	4.79	62.85	11.46	79.15
	ORE # 2	FEED		1009.05				0.06		0.15		0.24	
		TAILS		964.19				0.02		0.08		0.09	
D10	DOW 200	C1	2	13.72	141.95	13.72	141.95	4.00	68.88	5.85	42.61	15.20	59.02
	40 g/t	C2	6	5.51	107.75	19.23	249.7	3.16	76.22	5.13	52.44	12.79	69.6
	HEXANOL	C3	12	3.17	137.42	22.4	387.12	2.79	78.33	4.70	55.88	11.69	74.11
	10 g/t	C4	20	3.45	75.97	25.85	463.09	2.46	79.73	4.25	58.34	10.58	77.4
	ORE # 2	FEED		1002.20				0.05		0.14		0.25	
		TAILS		959.16				0.02		0.08		0.08	
D11	DOW 200	C1	2	14.09	141.26	14.09	141.26	4.85	72.09	5.97	42.48	18.10	57.31
	40 g/t	C2	6	5.69	107.63	19.78	248.89	3.83	79.93	5.51	55.08	15.36	68.27
	MIBC	C3	12	3.51	102.67	23.29	351.56	3.34	82.22	5.07	59.63	13.94	72.98
	10 g/t	C4	20	4.79	113.94	28.08	465.5	2.83	83.83	4.45	63.06	12.19	76.91
	ORE # 2	FEED		1005.47				0.06		0.14		0.25	
		TAILS		960.65				0.02		0.08		0.54	
D12	DOW 200	C1	2	14.56	141.92	14.56	141.92	4.89	71.79	7.88	48.05	18.30	59.93
	40 g/t	C2	6	6.43	111.05	20.99	252.97	3.76	79.51	6.67	58.63	15.04	71.02
	MIBC	C3	12	3.9	103.69	24.89	356.66	3.26	81.79	6.00	62.57	13.61	76.22
	10 g/t	C4	20	4.61	106.96	29.5	463.62	2.80	83.17	5.28	65.16	12.03	79.82
	ORE # 2	FEED		1011.20				0.05		0.14		0.25	
		TAILS		967.51				0.02		0.09		0.09	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
D13	DOW 250	C1	2	12.95	146.16	12.95	146.16	4.17	62.99	5.05	37.84	12.70	49.59
	50 g/t	C2	6	7.04	75.71	19.99	221.87	3.34	77.94	4.36	50.44	10.39	62.6
	ORE # 2	C3	12	2.61	101.39	22.6	323.26	3.01	79.36	4.11	53.71	9.64	65.7
		C4	20	3.28	78.28	25.88	401.54	2.67	80.57	3.74	55.99	8.80	68.66
		FEED		1003.30				0.06		0.14		0.25	
		TAILS		962.55				0.02		0.08		0.11	
D14	DOW 250	C1	2	12.41	126.76	12.41	126.76	4.27	63.6	5.48	37.01	16.70	53.91
	50 g/t	C2	6	7.98	97.05	20.39	223.81	3.10	75.94	4.78	53.02	13.11	69.54
	ORE # 2	C3	12	2.78	76.59	23.17	300.4	2.81	78.15	4.49	56.6	12.24	73.75
		C4	20	2.8	78.62	25.97	379.02	2.55	79.6	4.18	59.04	11.35	76.69
		FEED		1004.41				0.05		0.15		0.26	
		TAILS		963.36				0.02		0.08		0.09	
D15	DOW 200	C1	2	11.52	114.34	11.52	114.34	4.36	64.45	6.48	38.07	14.60	49.81
	50 g/t	C2	6	6.58	84.45	18.1	198.79	3.22	74.91	5.49	50.67	12.03	64.46
	ORE # 2	C3	12	2.85	70.98	20.95	269.77	2.87	77.11	5.05	53.97	11.17	69.28
		C4	20	3.98	100.56	24.93	370.33	2.46	78.82	4.46	56.69	9.94	73.37
		FEED		1006.02				0.05		0.14		0.24	
		TAILS		966.82				0.02		0.09		0.09	
D16	DOW 200	C1	2	11.64	111.58	11.64	111.58	4.13	63.93	7.02	39.92	14.40	52.02
	50 g/t	C2	6	5.77	86.62	17.41	198.2	3.18	73.57	6.06	51.52	12.41	67.06
	ORE # 2	C3	12	2.82	77.9	20.23	276.1	2.82	75.78	5.54	54.77	11.43	71.79
		C4	20	4.17	103.95	24.4	380.05	2.39	77.51	4.82	57.43	10.06	76.18
		FEED		1007.98				0.06		0.15		0.25	
		TAILS		968.56				0.02		0.09		0.08	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
E1	DOW 250	C1	2	15.07	107.45	15.07	107.45	5.19	72.09	8.37	45.48	18.60	54.48
	40 g/t	C2	6	5.99	92.03	21.06	199.48	4.25	82.49	8.52	64.7	16.18	66.24
	PENTANOL	C3	12	2.94	77.91	24	277.39	3.82	84.38	7.79	67.41	15.12	70.54
	10 g/t	C4	20	4.22	90.34	28.22	367.73	3.30	85.86	6.84	69.61	13.62	74.73
	ORE # 1	FEED		1015.98				0.08		0.18		0.32	
		TAILS		965.67				0.02		0.09		0.14	
E2	DOW 250	C1	2	16.08	117.67	16.08	117.67	5.88	73.86	9.23	50.93	18.50	51.57
	40 g/t	C2	6	7.32	109.73	23.4	227.4	4.56	83.3	7.95	63.88	15.93	64.65
	PENTANOL	C3	12	2.64	93.12	26.04	320.52	4.18	85.03	7.49	66.94	15.37	69.41
	10 g/t	C4	20	3.23	84.42	29.27	404.94	3.78	86.26	6.88	69.13	14.53	73.73
	ORE # 1	FEED		1004.68				0.08		0.19		0.35	
		TAILS		963.52				0.02		0.09		0.16	
E3	DOW 250	C1	2	16.81	120.24	16.81	120.24	5.51	72.89	9.71	56.3	24.90	53.62
	40 g/t	C2	6	9.21	109.25	26.02	229.49	4.12	84.33	8.02	71.99	19.80	66
	HEXANOL	C3	12	2.3	110.73	28.32	340.22	3.84	85.67	7.61	74.3	18.99	68.89
	10 g/t	C4	20	2.93	111.25	31.25	451.47	3.52	86.66	7.06	76.04	17.81	71.3
	ORE # 1	FEED		1005.76				0.08		0.02		0.34	
		TAILS		963.84				0.02		0.09		0.23	
E4	DOW 250	C1	2	17.45	155.76	17.45	155.76	5.20	74.52	9.76	54.94	23.50	57.68
	40 g/t	C2	6	7.99	85.61	25.44	241.37	4.01	83.68	8.02	65.88	19.29	69.04
	HEXANOL	C3	12	2.62	87.42	28.06	328.79	3.69	85.06	7.49	67.86	18.20	71.84
	10 g/t	C4	20	3.9	105.24	31.96	434.03	3.28	86.14	6.74	69.51	16.58	74.54
	ORE # 1	FEED		1017.44				0.08		0.19		0.33	
		TAILS		973.24				0.02		0.10		0.19	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
E5	DOW 250	C1	2	17.83	142.79	17.83	142.79	6.82	72.6	10.86	54.54	19.70	57.05
	40 g/t	C2	6	9.11	119.35	26.94	262.14	5.46	87.88	9.42	71.43	16.42	71.85
	MIBC	C3	12	4.81	120.65	31.75	382.79	4.73	89.79	8.36	74.73	14.94	77.03
	10 g/t	C4	20	3.4	96.44	35.15	479.23	4.31	90.48	7.68	76.01	13.91	79.44
	ORE # 1	FEED		1022.66				0.08		0.20		0.33	
		TAILS		978.28				0.02		0.09		0.13	
E6	DOW 250	C1	2	17.88	140.05	17.88	140.05	7.85	74.52	10.93	50.9	21.30	57.11
	40 g/t	C2	6	9.89	133.89	27.77	273.94	6.03	88.94	9.80	70.91	17.56	73.12
	MIBC	C3	12	4.09	106.53	31.86	380.47	5.34	90.4	8.89	73.79	16.36	78.17
	10 g/t	C4	20	3.04	97.75	34.9	478.22	4.91	91.01	8.24	74.96	15.41	80.64
	ORE # 1	FEED		1016.90				0.07		0.19		0.32	
		TAILS		967.14				0.02		0.10		0.13	
E7	DOW 200	C1	2	12.62	104.08	12.62	104.08	7.29	72.01	10.83	43.95	24.70	49.45
	40 g/t	C2	6	7.84	88.35	20.46	192.43	5.20	83.2	9.88	65.01	20.56	66.74
	PENTANOL	C3	12	4.44	89.01	24.9	281.44	4.40	85.79	8.71	69.74	18.45	72.89
	10 g/t	C4	20	3.93	95.04	28.83	376.48	3.85	86.84	7.73	71.66	16.65	76.16
	ORE # 1	FEED		1013.36				0.08		0.20		0.35	
		TAILS		969.42				0.02		0.09		0.16	
E8	DOW 200	C1	2	12.55	90.4	12.55	90.4	7.58	74.51	10.46	42.29	24.60	50.61
	40 g/t	C2	6	8.22	77.53	20.77	167.93	5.21	84.75	9.81	65.67	20.29	69.06
	PENTANOL	C3	12	3.1	84.2	23.87	252.13	4.61	86.23	8.95	68.83	18.79	73.53
	10 g/t	C4	20	4.64	106.88	28.51	359.01	3.91	87.4	7.73	71	16.56	77.41
	ORE # 1	FEED		1021.88				0.68		0.16		0.36	
		TAILS		977.39				0.02		0.09		0.14	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
E9	DOW 200	C1	2	15.22	98.03	15.22	98.03	6.97	76.67	10.90	52.12	25.30	60.13
	40 g/t	C2	6	7.95	108.28	23.17	206.31	5.12	85.64	9.09	66.14	20.39	73.79
	HEXANOL	C3	12	3.48	101.38	26.65	307.69	4.53	87.21	8.23	68.89	18.60	77.4
	10 g/t	C4	20	3.99	116.73	30.64	424.42	3.98	88.02	7.30	70.31	16.72	79.99
	ORE # 1	FEED		1012.10				0.08		0.20		0.34	
		TAILS		967.35				0.02		0.10		0.13	
E10	DOW 200	C1	2	15.34	86.45	15.34	86.45	6.98	77.6	10.28	50.45	23.10	56.67
	40 g/t	C2	6	8.12	116.48	23.46	202.93	5.07	86.32	8.94	67.09	19.05	71.48
	HEXANOL	C3	12	3.76	96.84	27.22	299.77	4.45	87.87	8.05	70.12	17.37	75.61
	10 g/t	C4	20	4.17	122.93	31.39	422.7	3.90	88.7	7.14	71.7	15.66	78.62
	ORE # 1	FEED		1012.16				0.08		0.20		0.34	
		TAILS		965.01				0.02		0.09		0.14	
E11	DOW 200	C1	2	16.31	135.62	16.31	135.62	7.33	78.07	10.80	52.52	24.20	57.38
	40 g/t	C2	6	7.25	105.22	23.56	240.84	5.64	86.72	9.76	68.55	20.85	71.4
	MIBC	C3	12	3.08	90.7	26.64	331.54	5.06	88	8.93	70.97	19.17	74.23
	10 g/t	C4	20	5.4	113.35	32.04	444.89	4.26	89.13	7.64	73.02	16.70	77.77
	ORE # 1	FEED		1016.00				0.08		0.19		0.34	
		TAILS		967.89				0.02		0.09		0.16	
E12	DOW 200	C1	2	16.39	110.94	16.39	110.94	8.97	79.98	11.32	48.63	28.30	57.61
	40 g/t	C2	6	8.26	125.92	24.65	236.86	6.63	88.86	11.09	71.66	24.14	73.92
	MIBC	C3	12	3.41	86.09	28.06	322.95	5.91	90.22	10.15	74.66	22.22	77.45
	10 g/t	C4	20	5.14	123.04	33.2	445.99	5.05	91.15	8.79	76.48	19.49	80.39
	ORE # 1	FEED		1015.98				0.07		0.19		0.34	
		TAILS		965.67				0.02		0.09		0.16	

Run No.	Frother Type and Dosage	Sample ID	Time Mins	Mass Pull g	Water recovery g	Cum Mass g	Cum Water g	Copper grade (%)	Copper Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Sulphur Grade (%)	Sulphur Recovery (%)
E13	DOW 250	C1	2	13.54	105.41	13.54	105.41	6.57	75.71	10.44	52.83	22.20	55.96
	50 g/t	C2	6	5.24	104.84	18.78	210.25	5.17	82.6	8.83	61.97	18.79	65.68
	ORE # 1	C3	12	3.37	91.85	22.15	302.1	4.49	84.65	7.87	65.12	17.04	70.26
		C4	20	4.14	81.06	26.29	383.16	3.84	85.97	6.84	67.23	15.12	73.99
		FEED		1004.68				0.08		0.20		0.33	
		TAILS		963.52				0.02		0.09		0.15	
E14	DOW 250	C1	2	13.69	121.24	13.69	121.24	6.29	74.43	10.08	50.19	21.40	53.1
	50 g/t	C2	6	6.56	135.24	20.25	256.48	4.71	82.43	8.26	60.86	17.77	65.22
	ORE # 1	C3	12	2.74	77.15	22.99	333.63	4.23	84.04	7.57	63.34	16.47	68.61
		C4	20	3.82	59.78	26.81	393.41	3.68	85.3	6.70	65.33	15.06	73.19
		FEED		1005.76				0.07		0.19		0.36	
		TAILS		963.84				0.02		0.10		0.15	
E15	DOW 200	C1	2	12.11	108.08	12.11	108.08	7.65	66.2	10.93	44.27	23.70	46.14
	50 g/t	C2	6	6.46	88.28	18.57	196.36	5.66	75.08	9.25	57.46	20.15	60.16
	ORE # 1	C3	12	2.97	81.1	21.54	277.46	4.98	76.65	8.41	60.56	18.43	63.83
		C4	20	4.79	71.11	26.33	348.57	4.14	77.8	7.13	62.77	15.95	67.5
		FEED		1017.44				0.07		0.18		0.34	
		TAILS		973.24				0.02		0.09		0.14	
E16	DOW 200	C1	2	12.14	109.65	12.14	109.65	7.47	74.42	10.92	47.59	22.90	50.57
	50 g/t	C2	6	6.44	83.31	18.58	192.96	5.47	83.41	9.23	61.55	19.50	65.92
	ORE # 1	C3	12	3.1	61.82	21.68	254.78	4.79	85.3	8.35	65	17.74	69.97
		C4	20	4.67	86.36	26.35	341.14	4.00	86.58	7.12	67.4	15.37	73.66
		FEED		1022.66				0.07		0.18		0.34	
		TAILS		978.28				0.02		0.09		0.15	

APPENDIX B: BUBBLE SIZE DISTIBUTION

It was shown in section 4.5 that the mean bubble size in a solution containing pure frother as well as blends continues to decreases from low concentrations until it reaches a limiting value. This trend is also matched in the bubble size distribution. Figure 5.1 shows the bubble size distribution for 1-pentanol and Dow 200 at the total dosage of 5 ppm (2 ppm Dow 200 with 3 ppm 1-pentanol). The results show a wide range of bubble size distribution at this initial dosage. The bubble size distribution then start to converge into a narrower unimodal distribution as the total concentration of the frother is increased. This can be seen in Figure 5.2 which represents a total frother concentration of 10 ppm. Figure 5.3 representing a total frother concentration of 15 ppm and Figure 5.5 representing a total frother concentration of 20 ppm. As the total concentration of the blend is further increased the bubble size distribution again start to assume a wide range of size distribution as it can be seen in Figure 5.6 which represent a total frother concentration of 25 ppm and Figure 5.7 representing a total frother concentration of 30 ppm. The same trend was observed with the results involving the use of 1-hexanol and MIBC frothers and the results are shown in the appendix. Tests were also conducted using Dow 250 with blends of 1-pentanol, 1-hexanol and MIBC. The same trend as that of Dow 200 was observed and the results are shown from Figures 5.8 to 5.33.

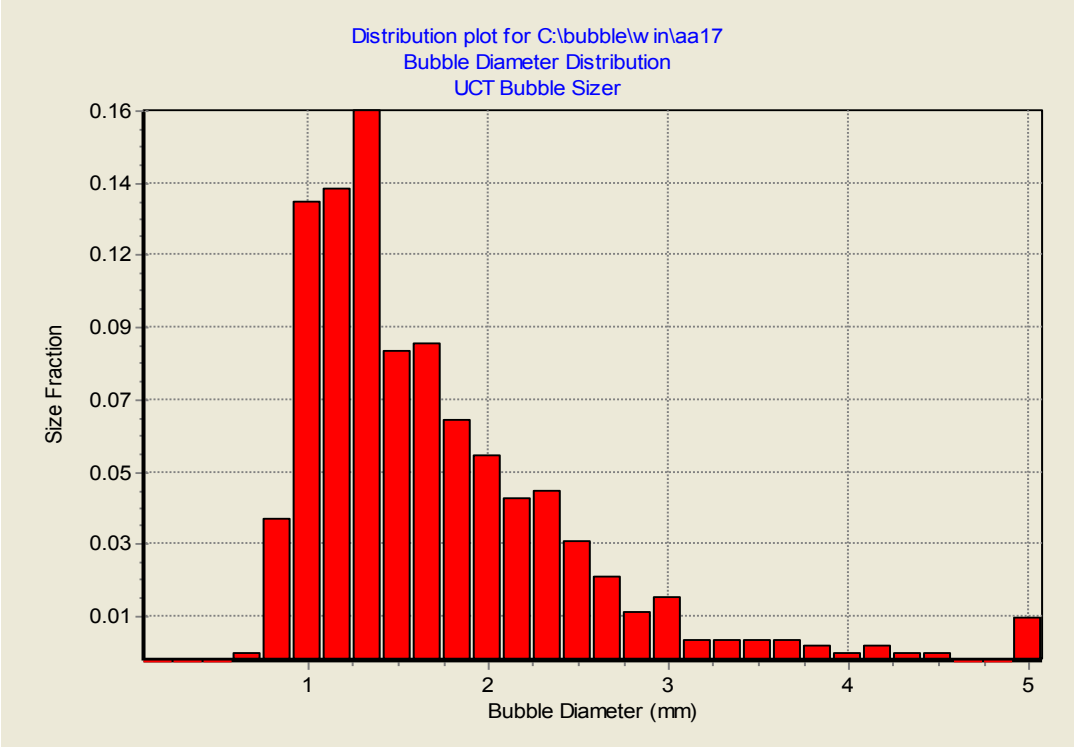

Figure 5.1 Bubble size distributions for 1-pentanol and Dow 200 at a total frother dosage of 5 ppm

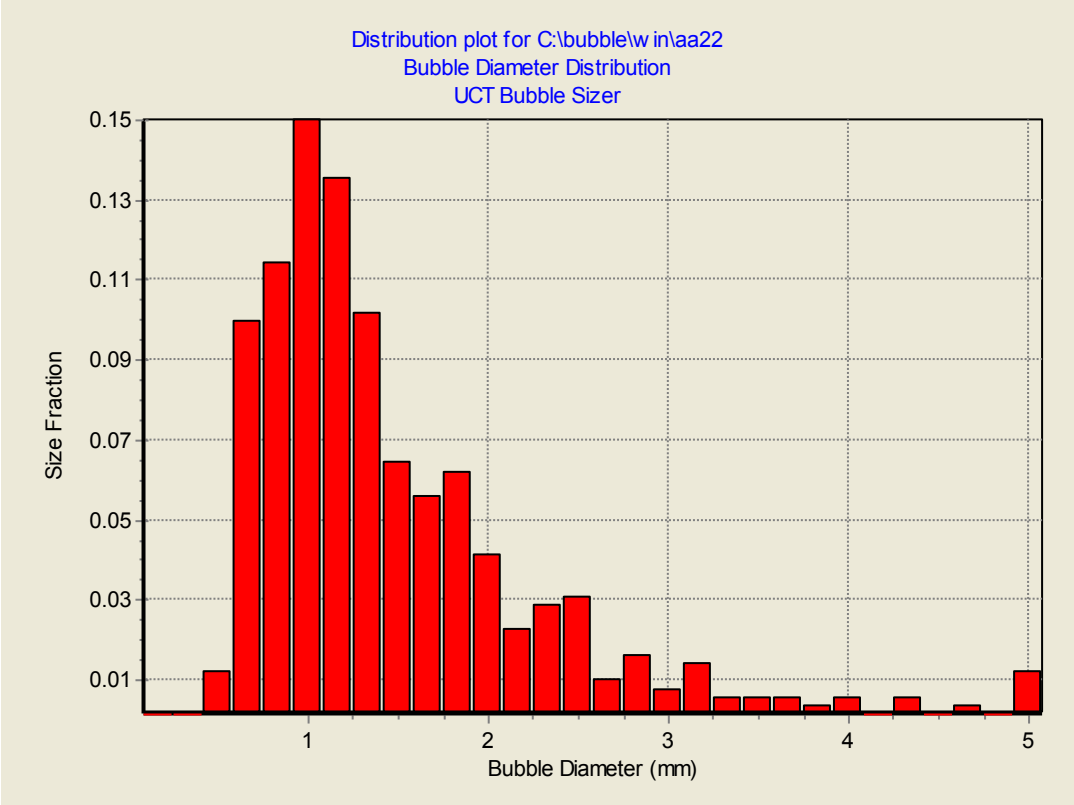

Figure 5.2 Bubble size distributions for 1-pentanol and Dow 200 at a total frother dosage of 10 ppm

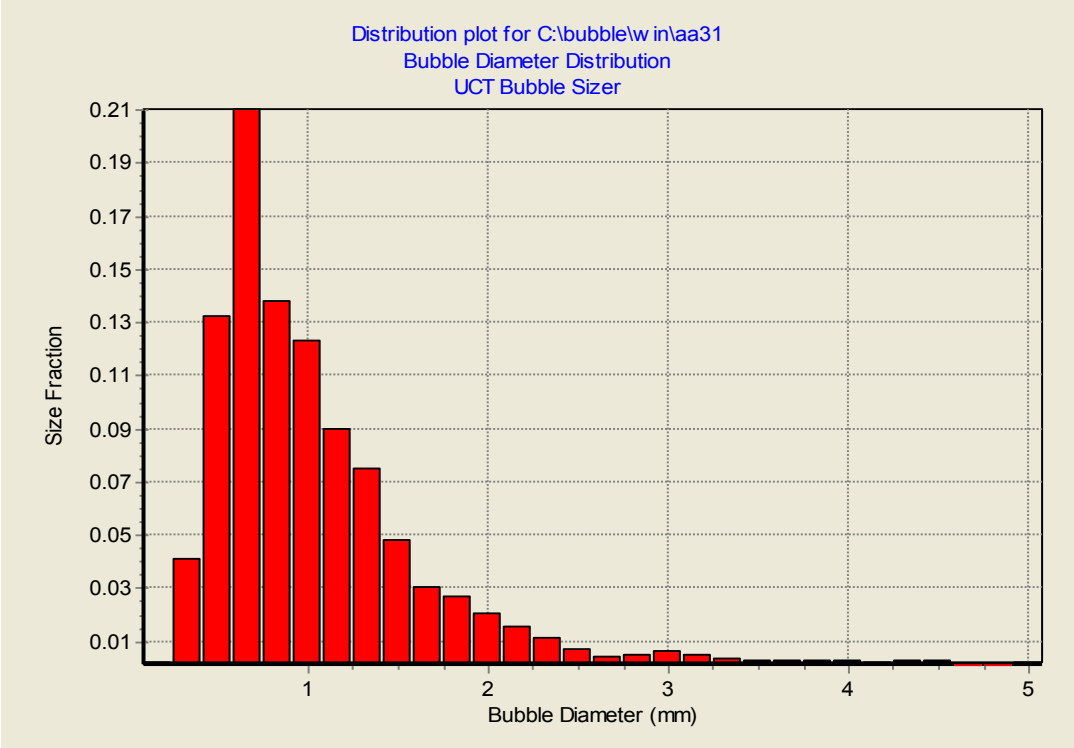

Figure 5.3 Bubble size distributions for 1-pentanol and Dow 200 at a total frother dosage of 15 ppm

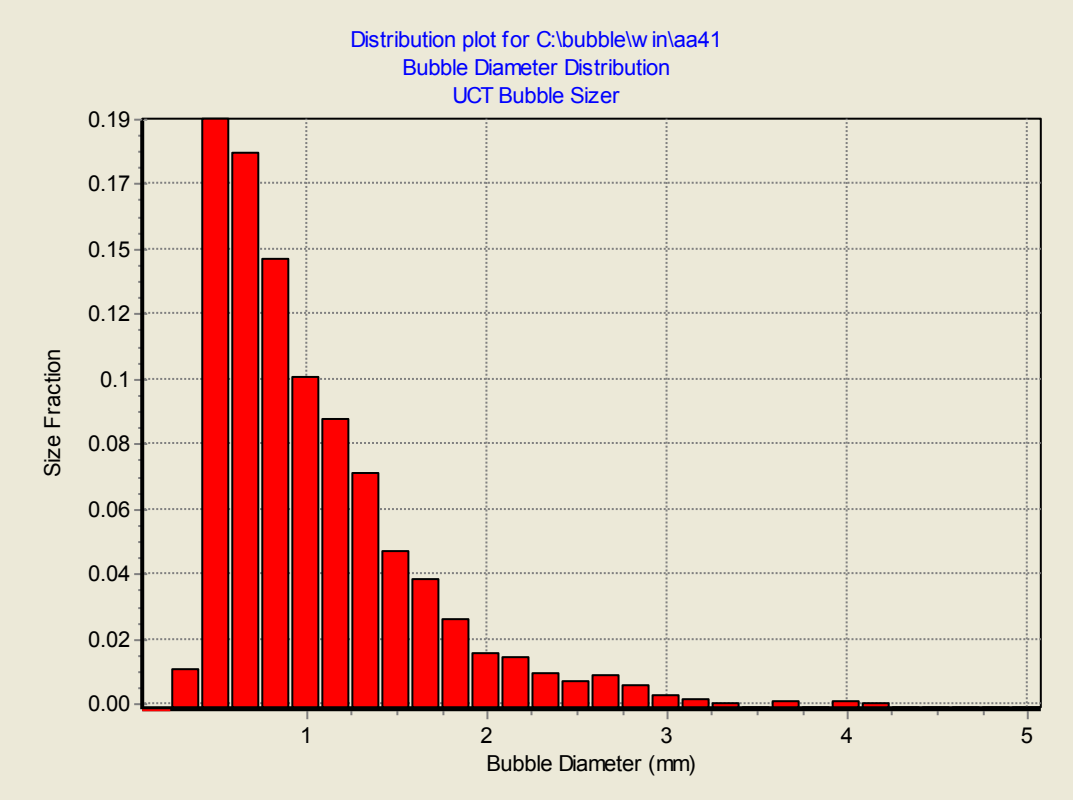

Figure 5.4 Bubble size distributions for 1-pentanol and Dow 200 at a total frother dosage of 20 ppm

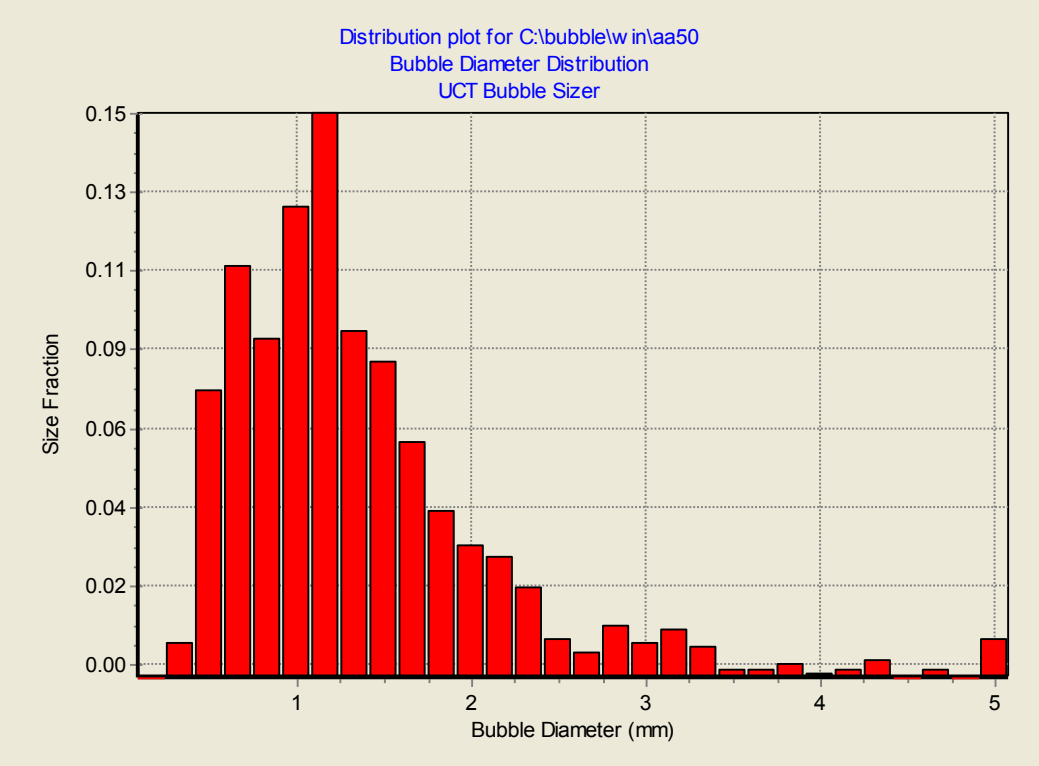

Figure 5.5 Bubble size distributions for 1-pentanol and Dow 200 at a total frother dosage of 25 ppm

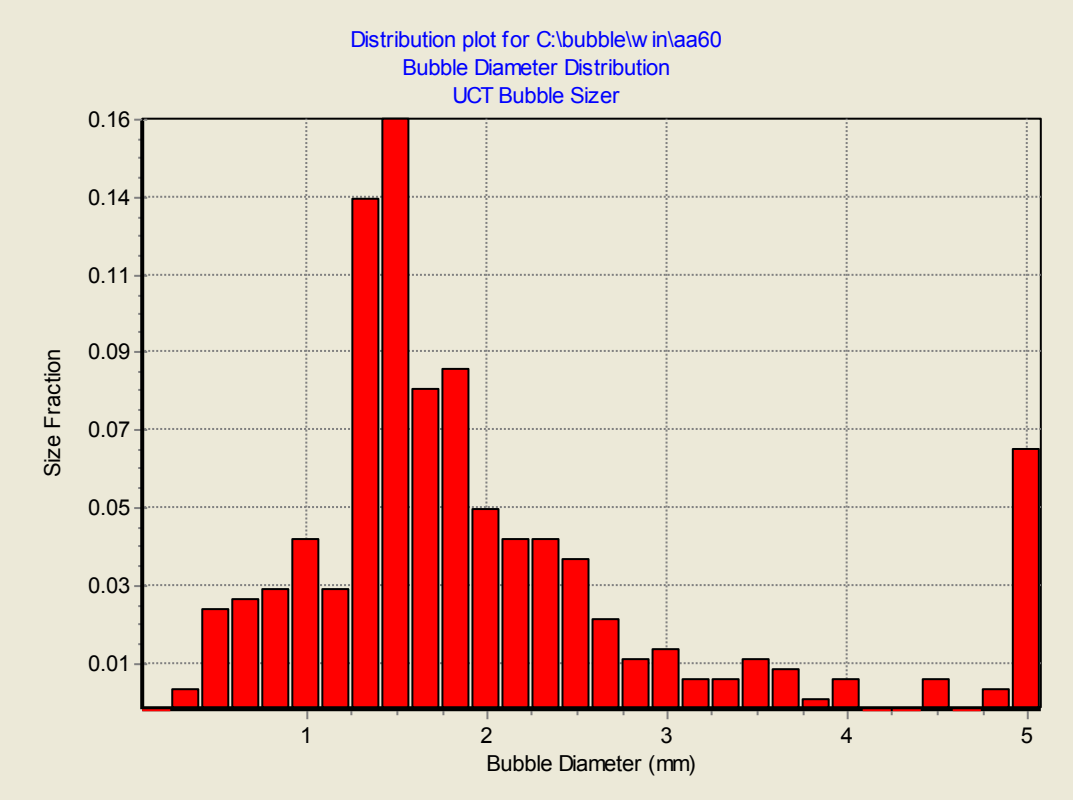

Figure 5.6 Bubble size distributions for 1-pentanol and Dow 200 at a total dosage of 30 ppm

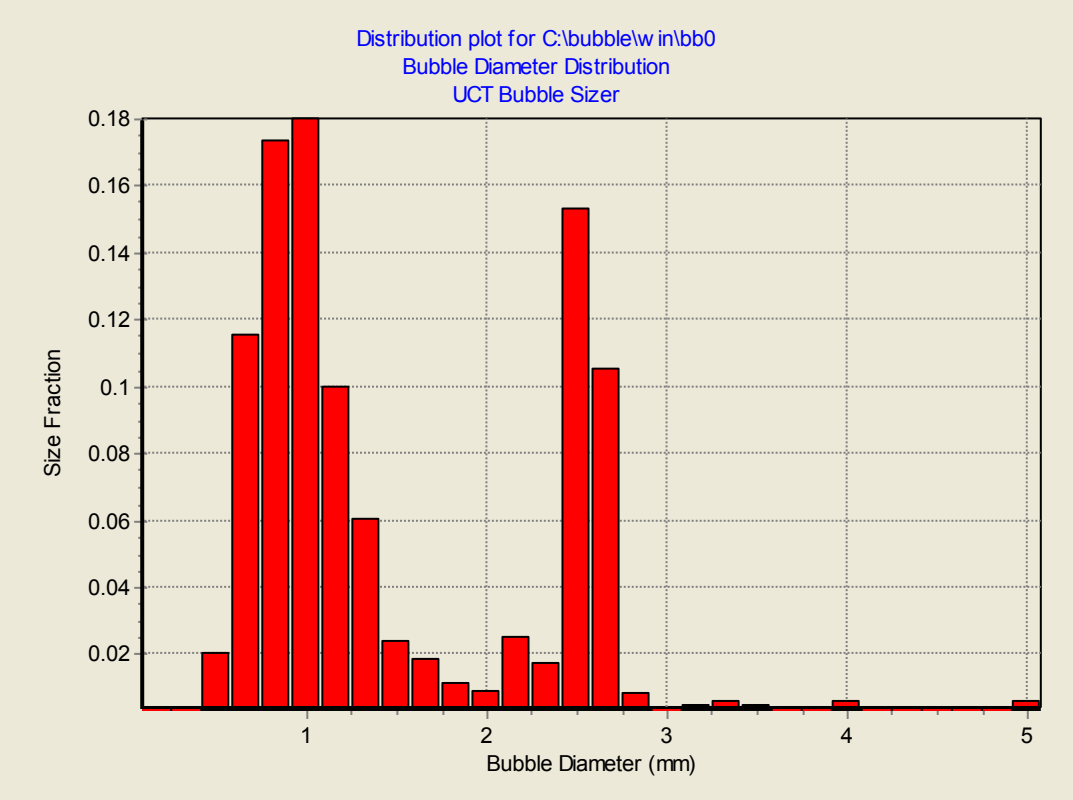

Figure 5.7 Bubble size distributions for MIBC and Dow 200 at a total dosage of 5 ppm

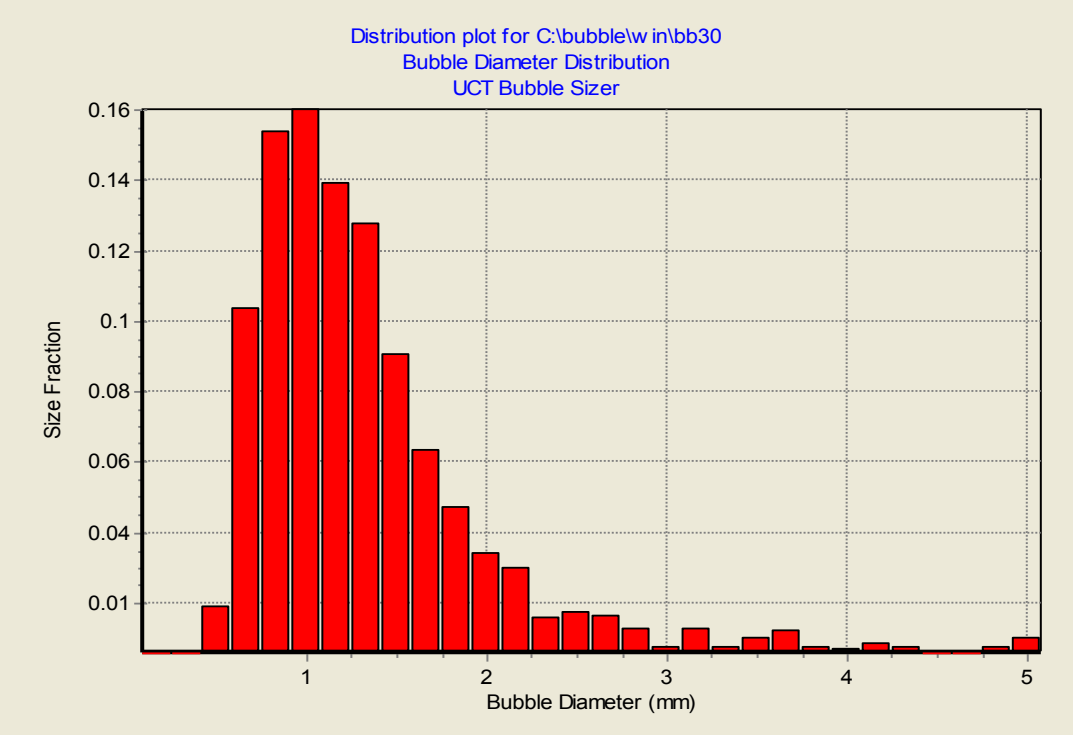

Figure 5.8 Bubble size distributions for MIBC and Dow 200 at a total dosage of 10 ppm

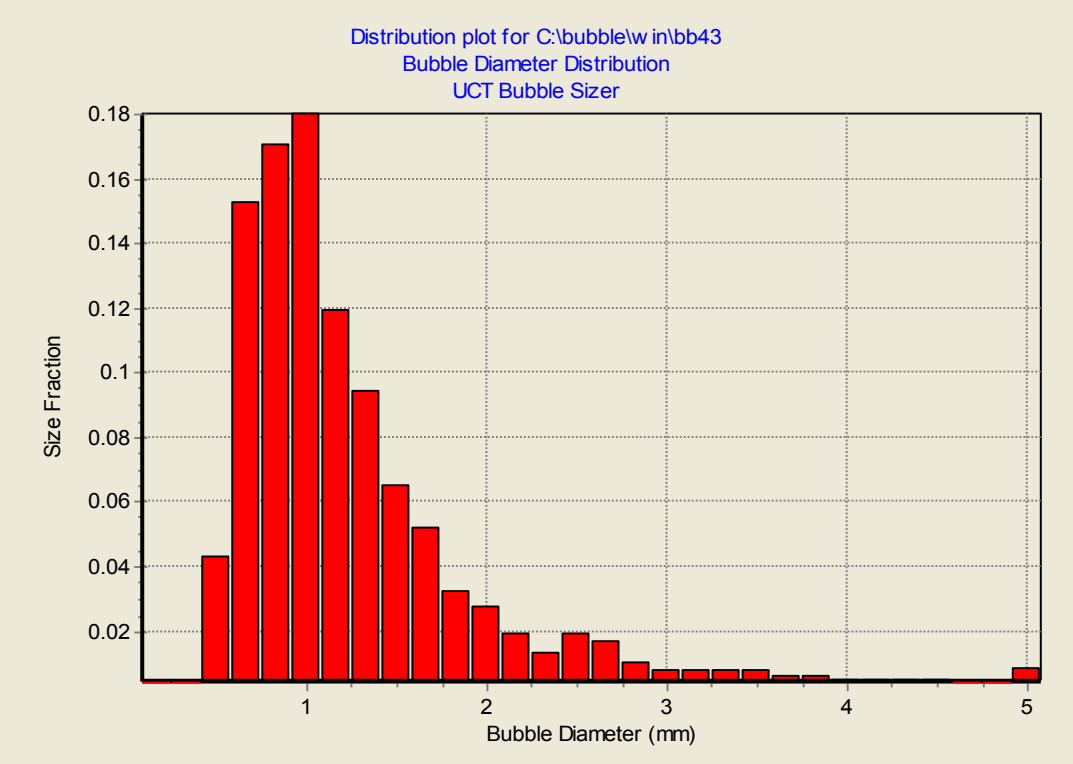

Figure 5.9 Bubble size distributions for MIBC and Dow 200 at a total dosage of 15 ppm

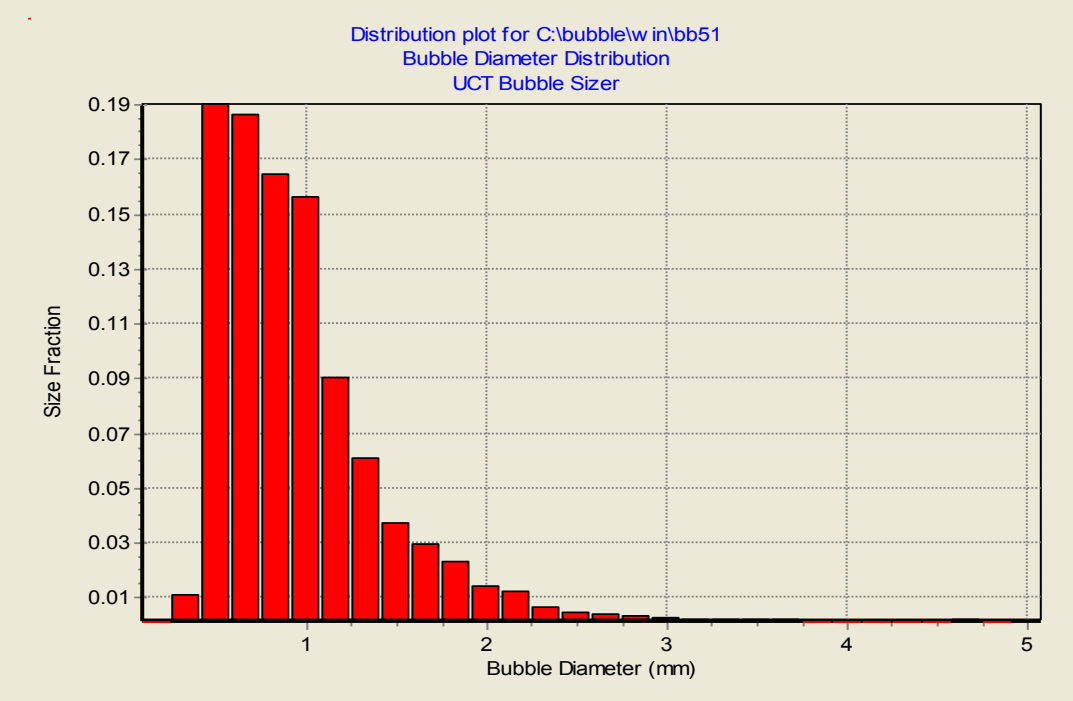

Figure 5.10 Bubble size distributions for MIBC and Dow 200 at a total dosage of 20 ppm

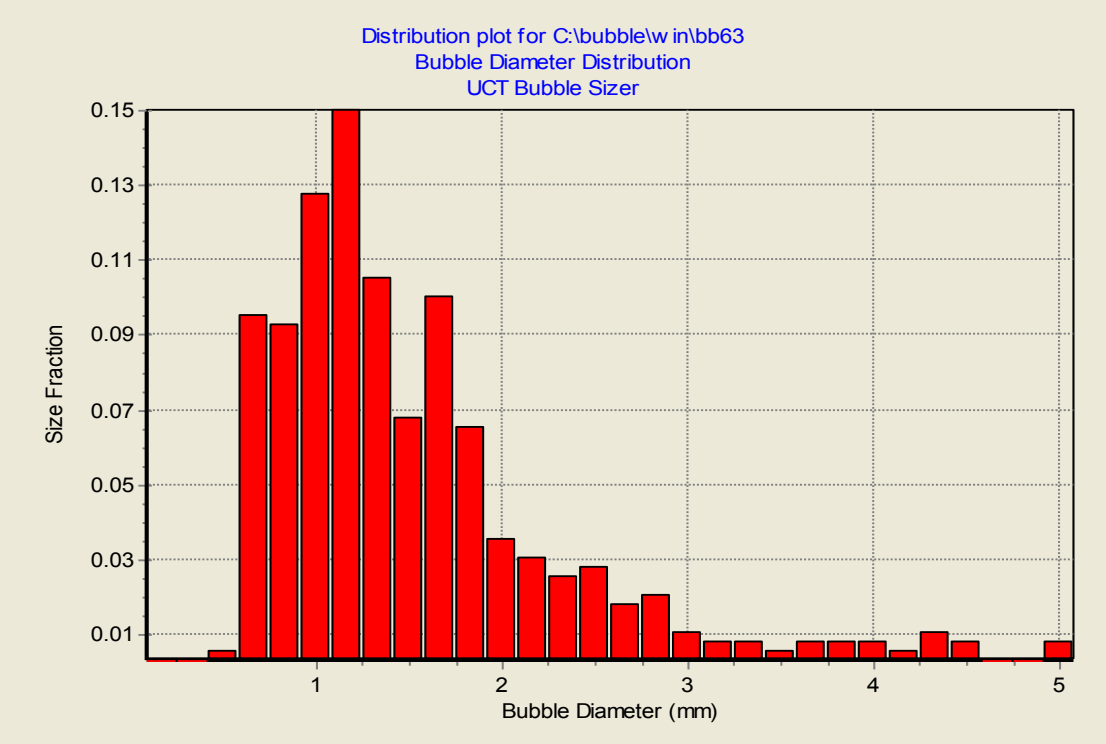

Figure 5.11 Bubble size distributions for MIBC and Dow 200 at a total dosage of 30 ppm

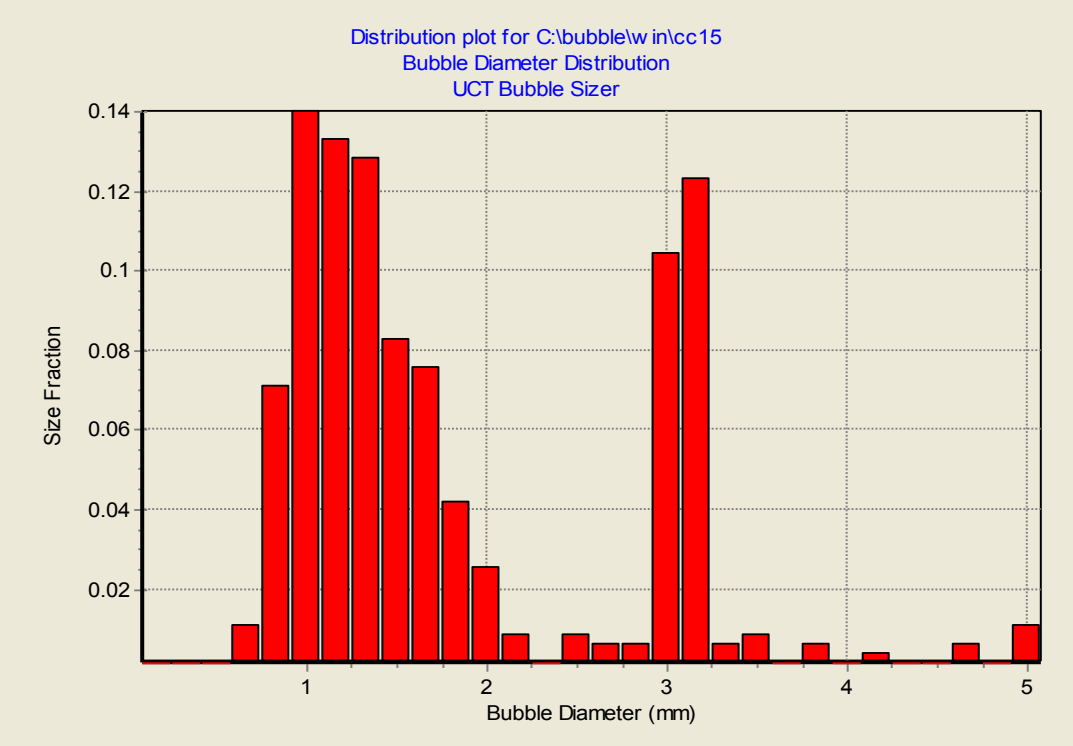

Figure 5.12 Bubble size distributions for 1-hexanol and Dow 200 at a total dosage of 5 ppm

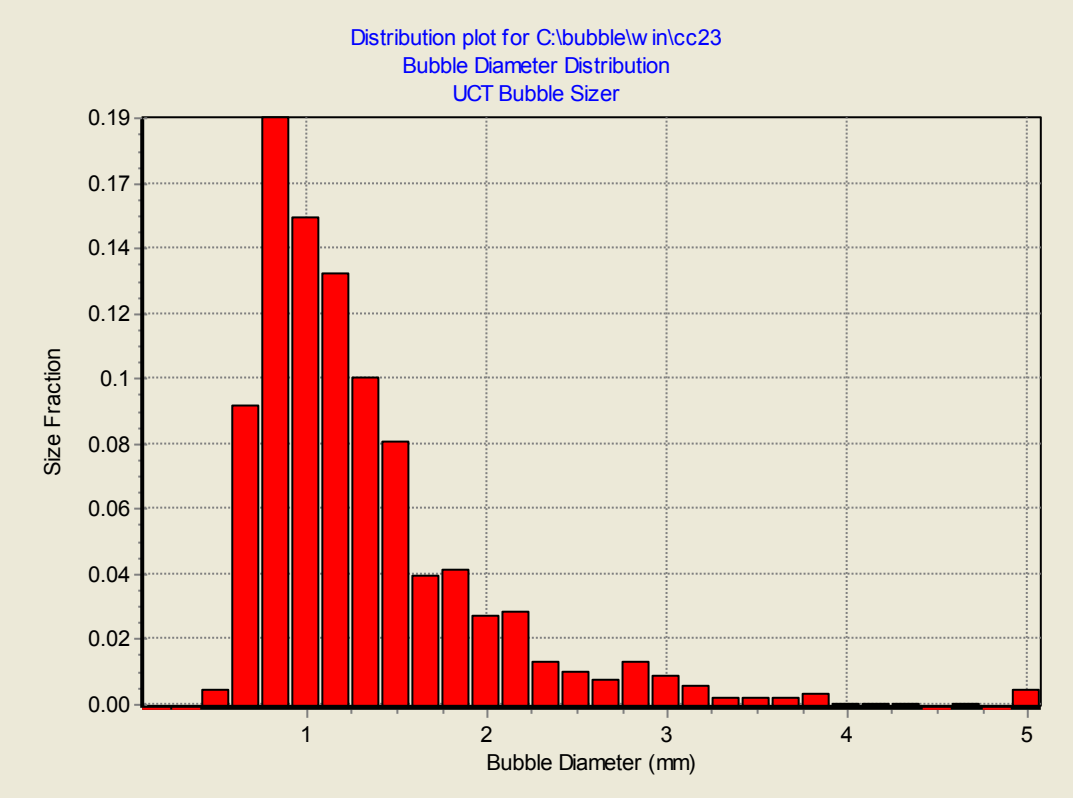

Figure 5.13 Bubble size distributions for 1-hexanol and Dow 200 at a total dosage of 10 ppm

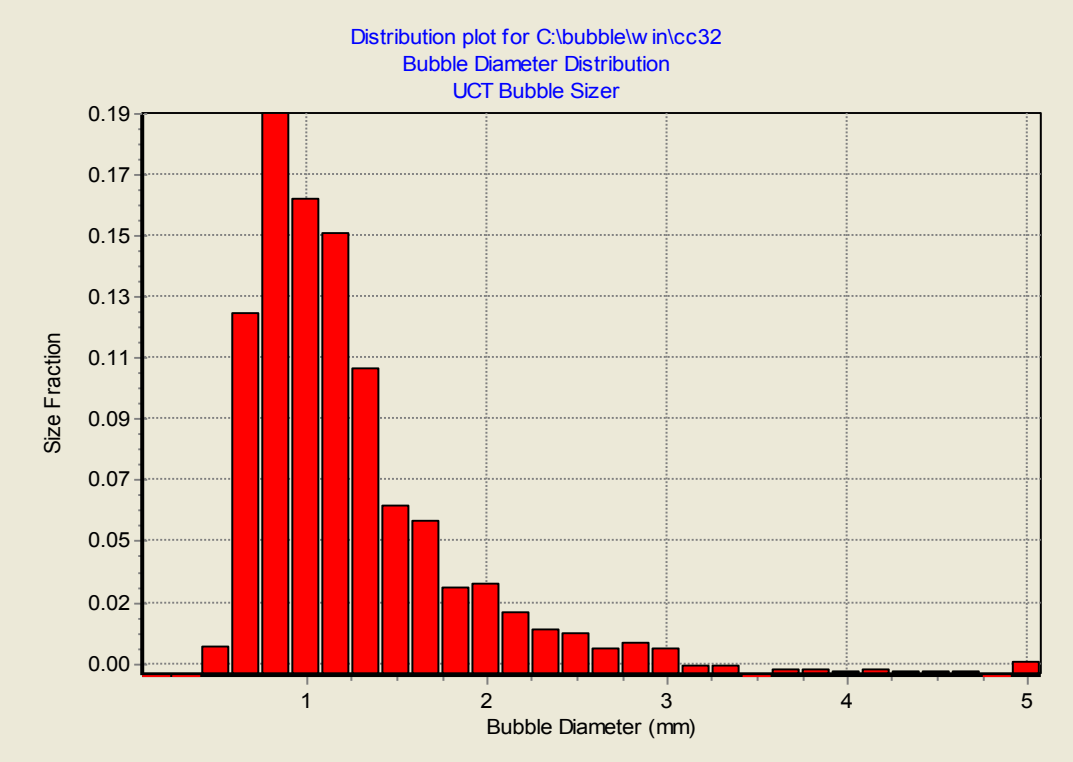

Figure 5.14 Bubble size distributions for 1-hexanol and Dow 200 at a total dosage of 15 ppm

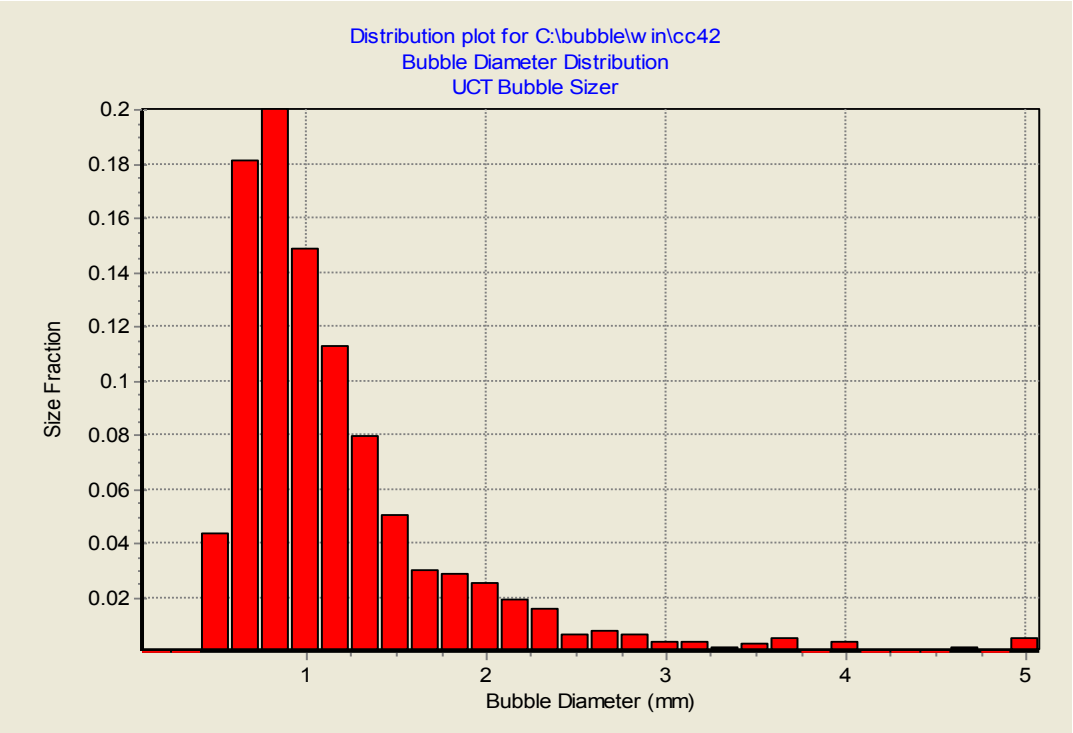

Figure 5.15 Bubble size distributions for 1-hexanol and Dow 200 at a total dosage of 20 ppm

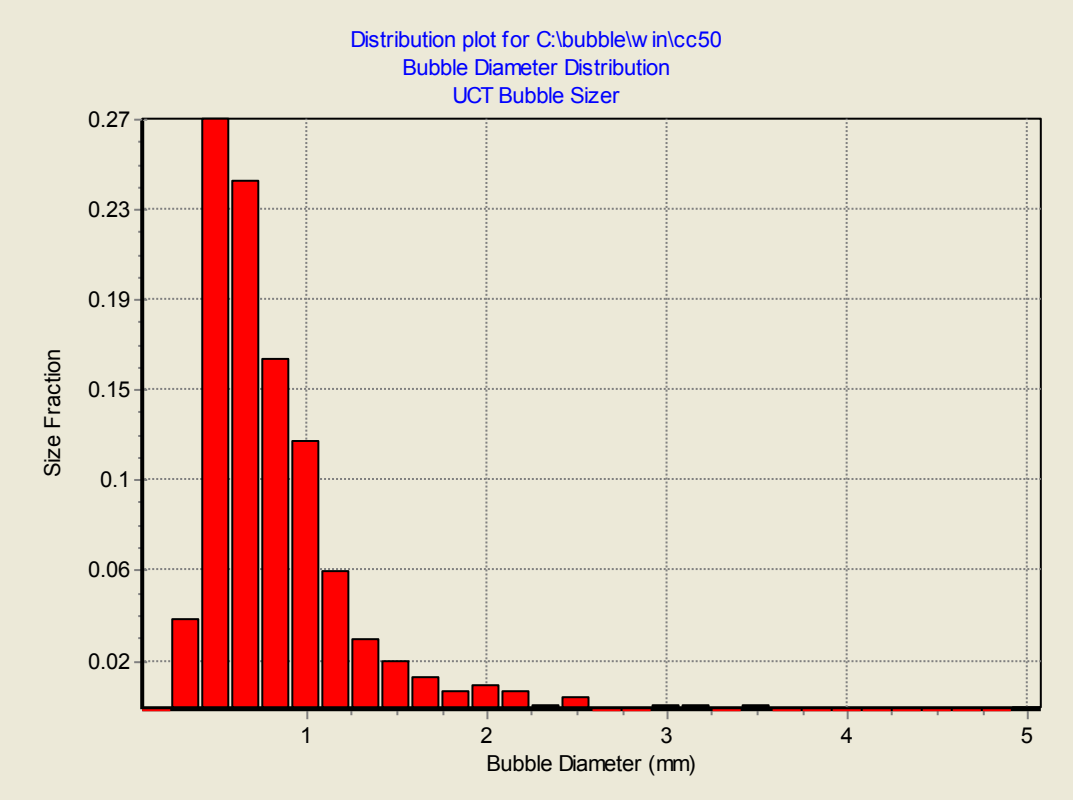

Figure 5.16 Bubble size distributions for 1-hexanol and Dow 200 at a total dosage of 25 ppm

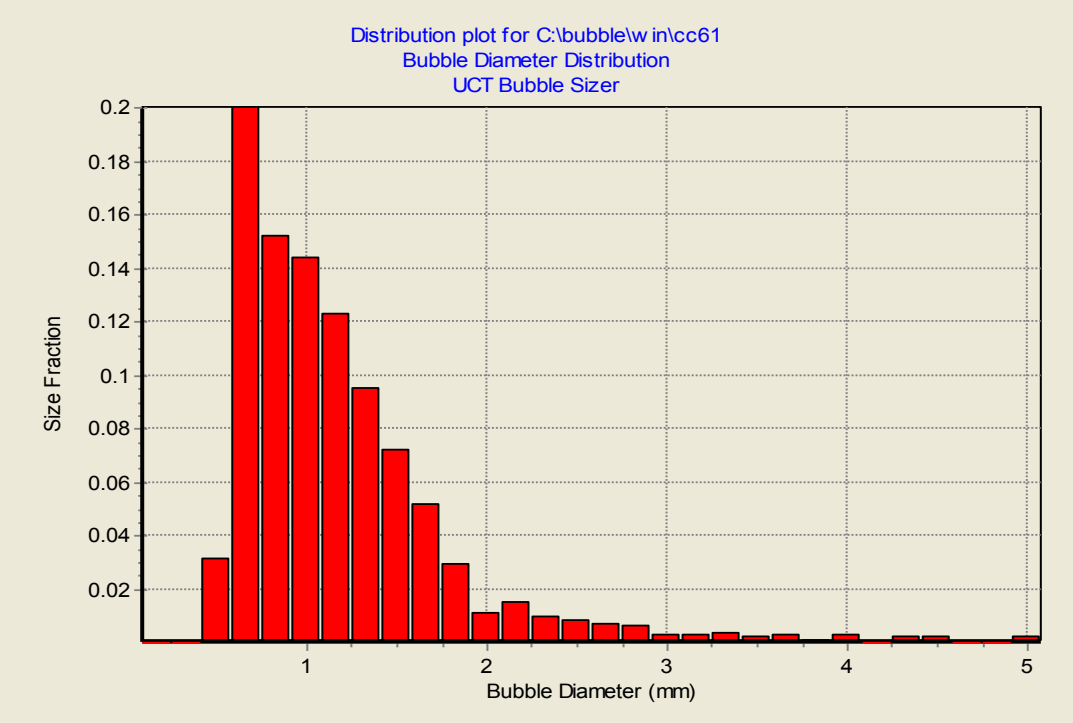

Figure 5.17 Bubble size distributions for 1-hexanol and Dow 200 at a total dosage of 30 ppm

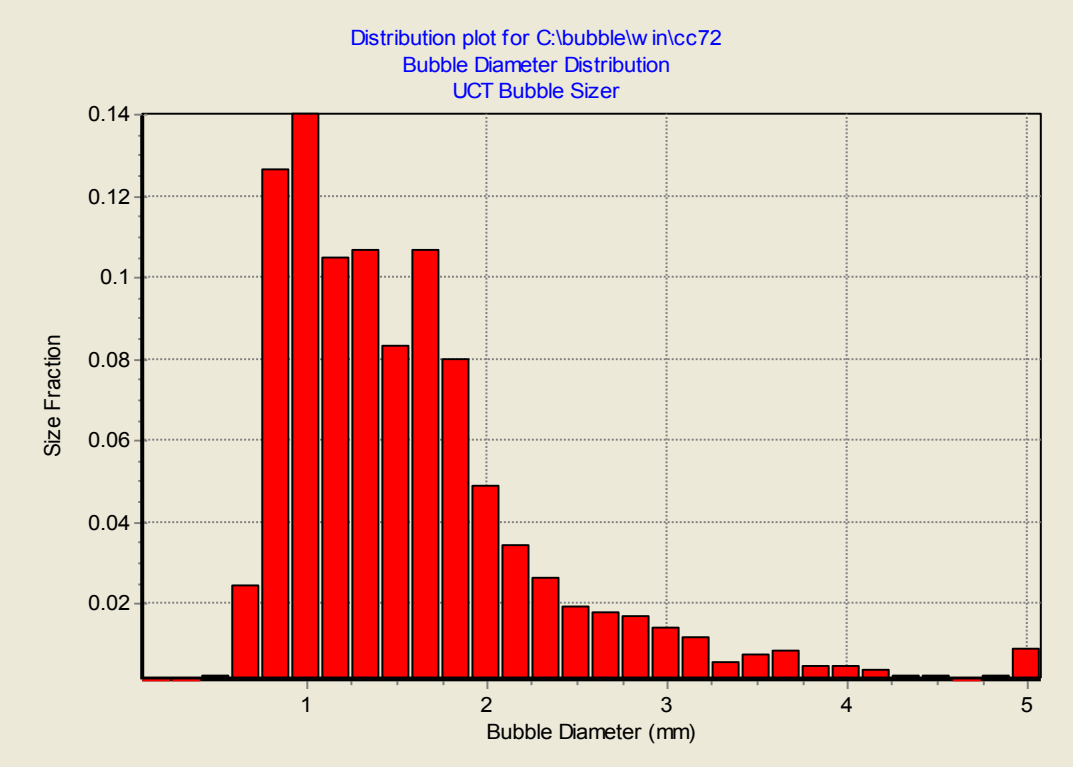

Figure 5.18 Bubble size distributions for 1-hexanol and Dow 200 at a total dosage of 30 ppm

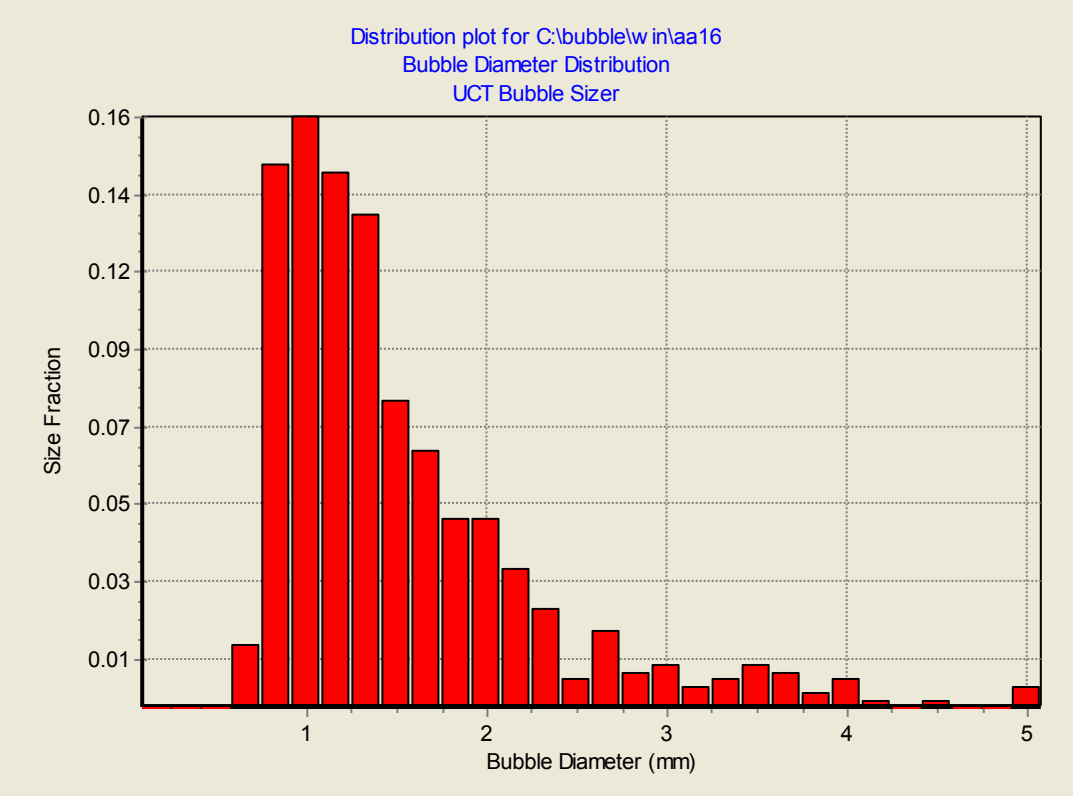

Figure 5.19 Bubble size distributions for 1-pentanol and Dow 250 at a total dosage of 5 ppm

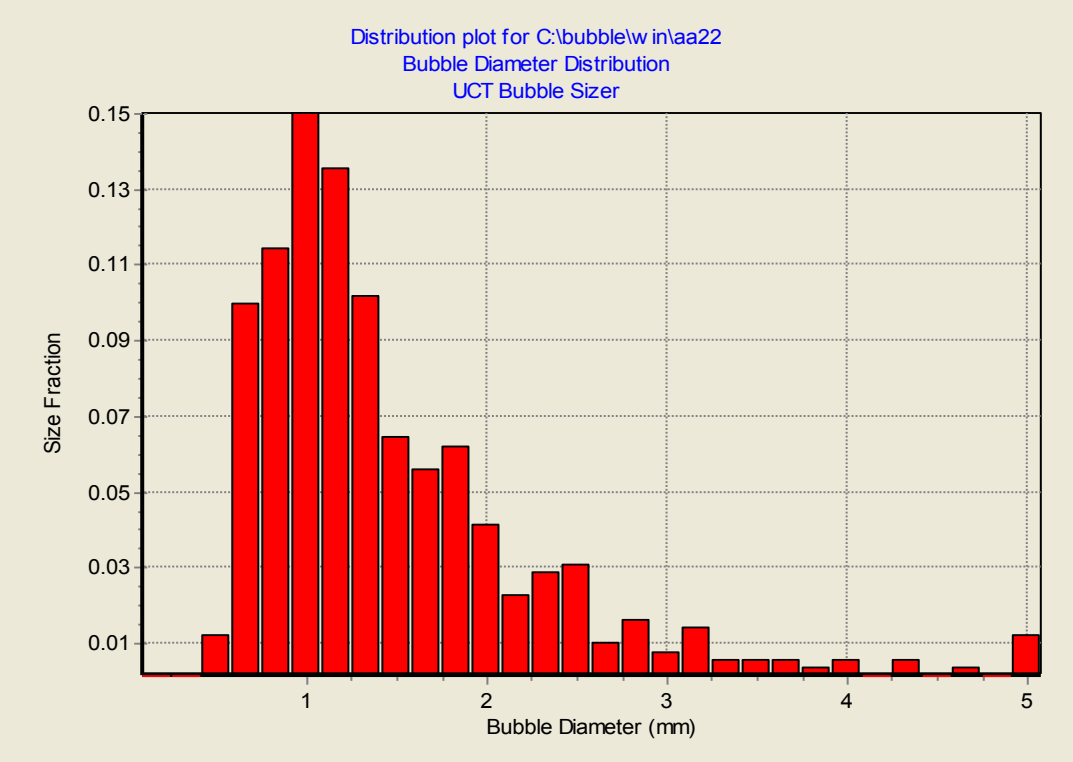

Figure 5.20 Bubble size distributions for 1-pentanol and Dow 250 at a total dosage of 10 ppm

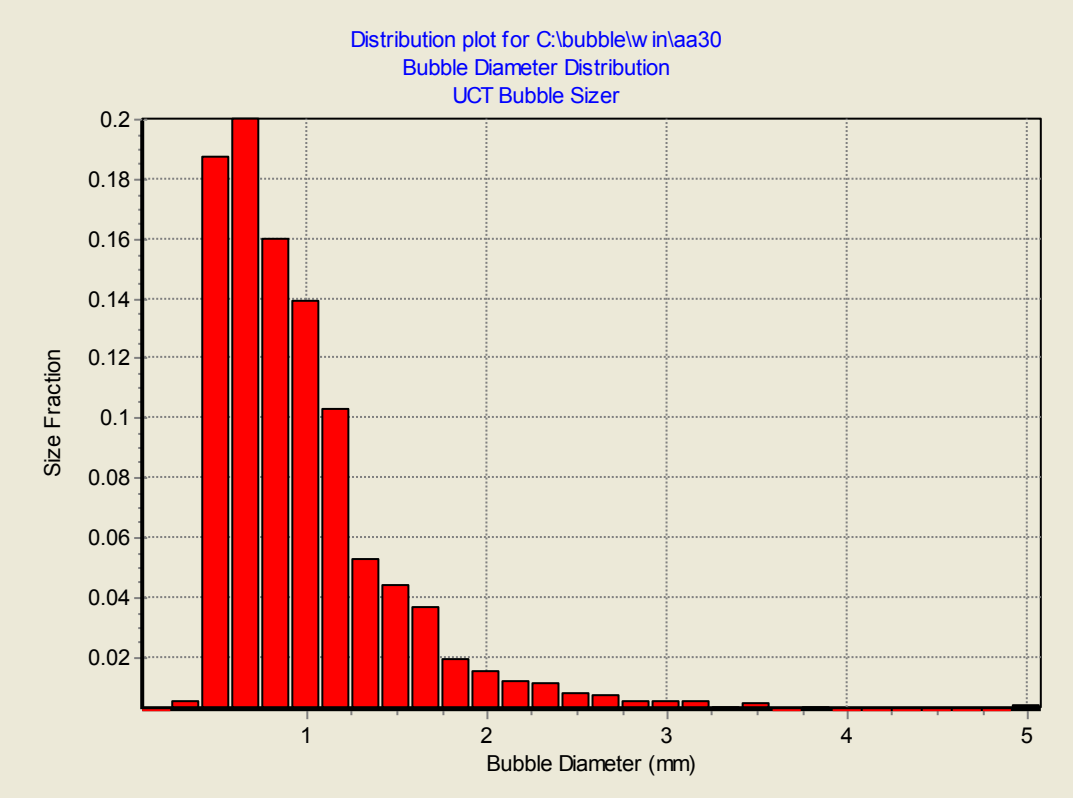

Figure 5.21 Bubble size distributions for 1-pentanol and Dow 250 at a total dosage of 20 ppm

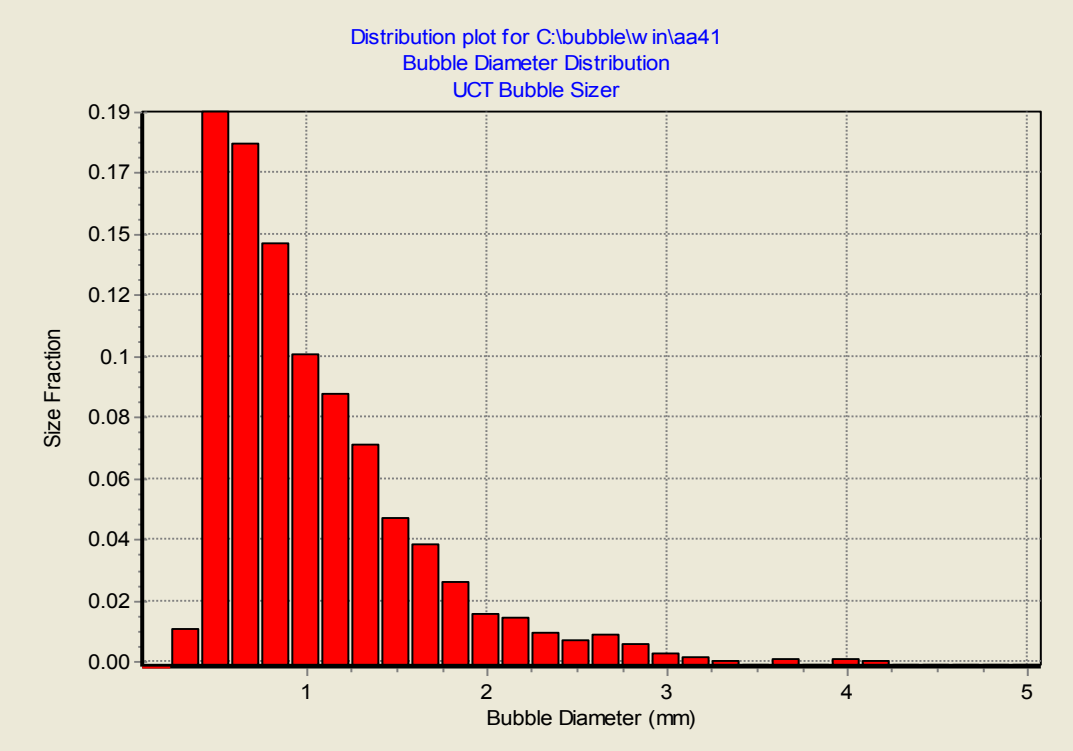

Figure 5.22 Bubble size distributions for 1-pentanol and Dow 250 at a total dosage of 25 ppm

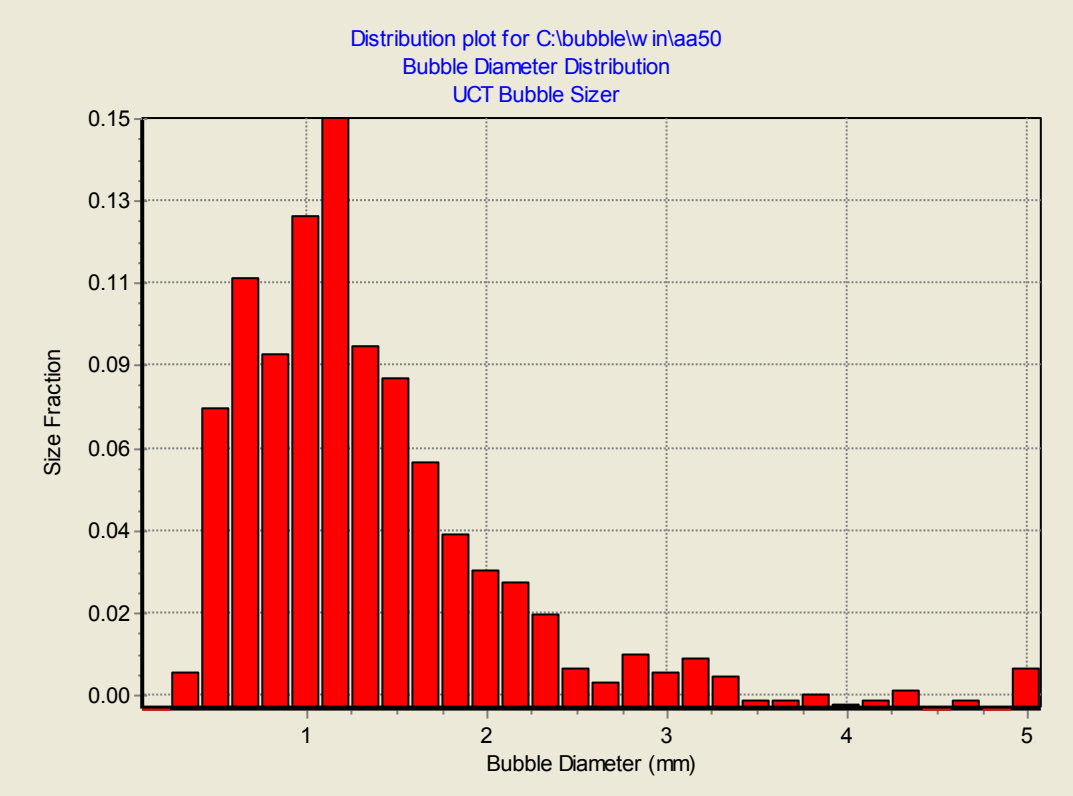

Figure 5.23 Bubble size distributions for 1-pentanol and Dow 250 at a total dosage of 30 ppm

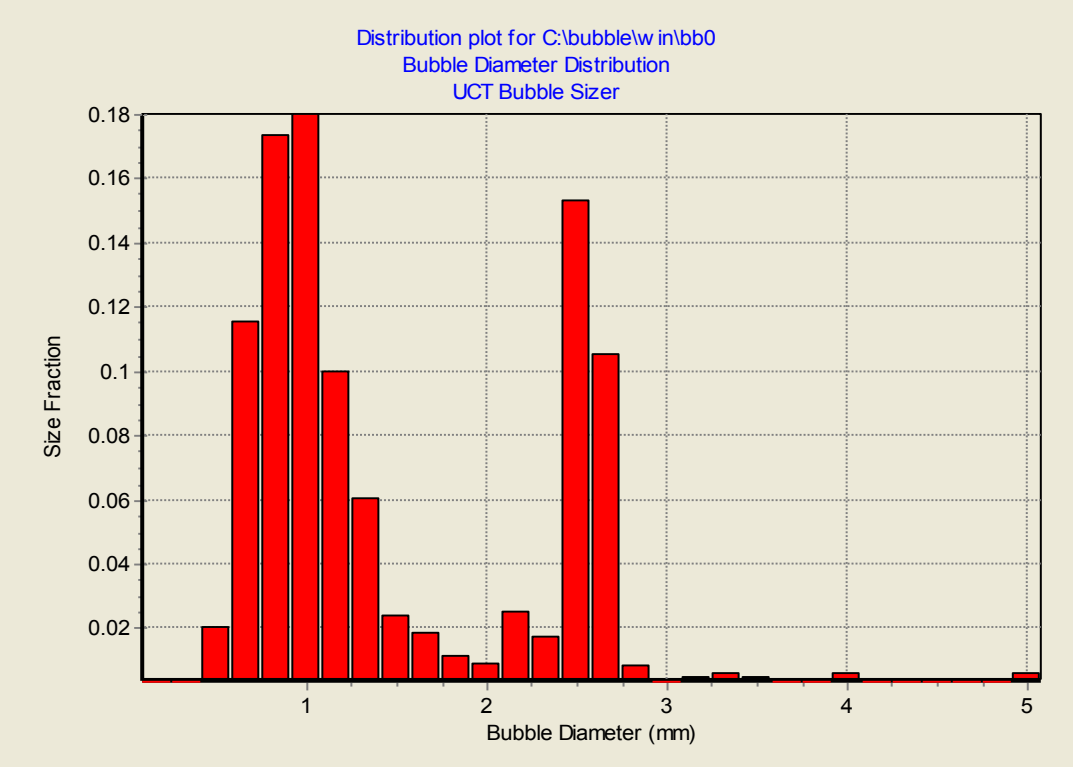

Figure 5.24 Bubble size distributions for MIBC and Dow 250 at a total dosage of 5 ppm

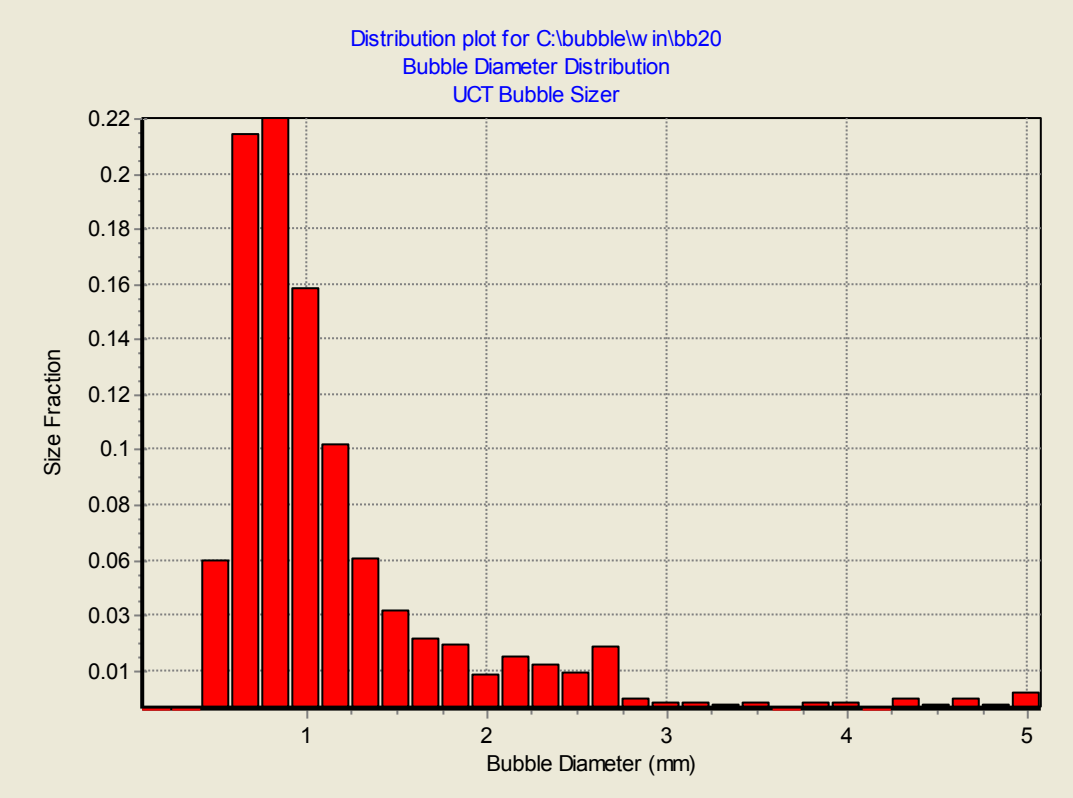

Figure 5.25 Bubble size distributions for MIBC and Dow 250 at a total dosage of 10 ppm

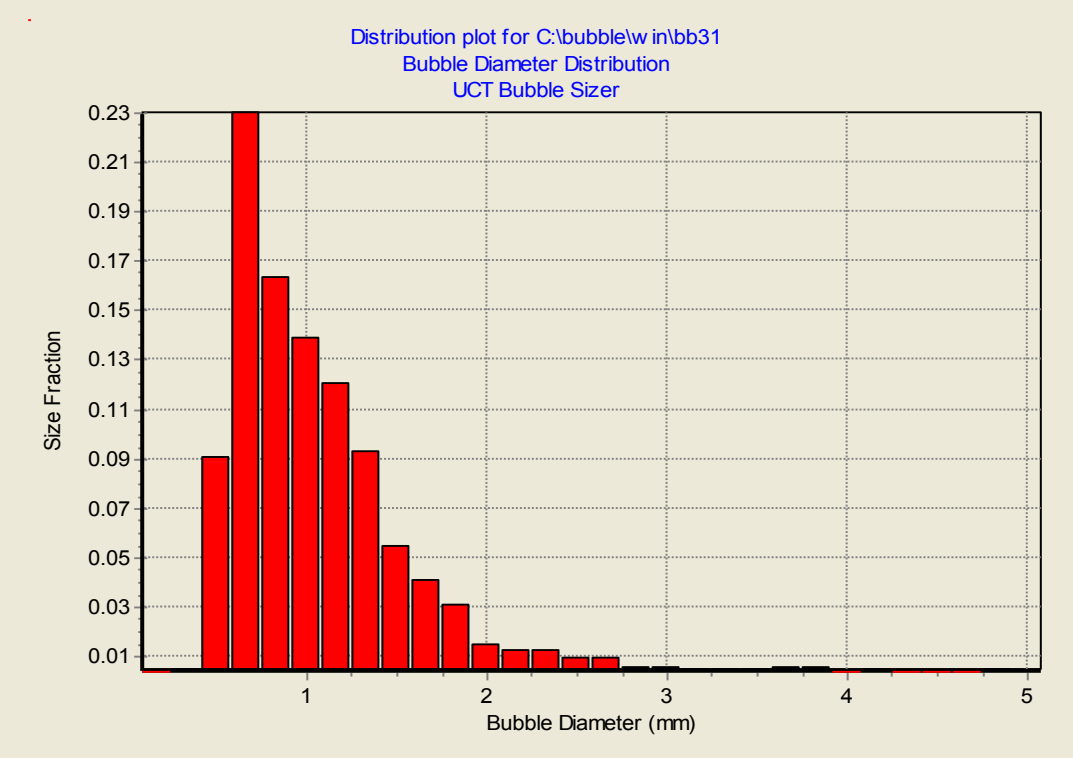

Figure 5.26 Bubble size distributions for MIBC and Dow 250 at a total dosage of 15 ppm

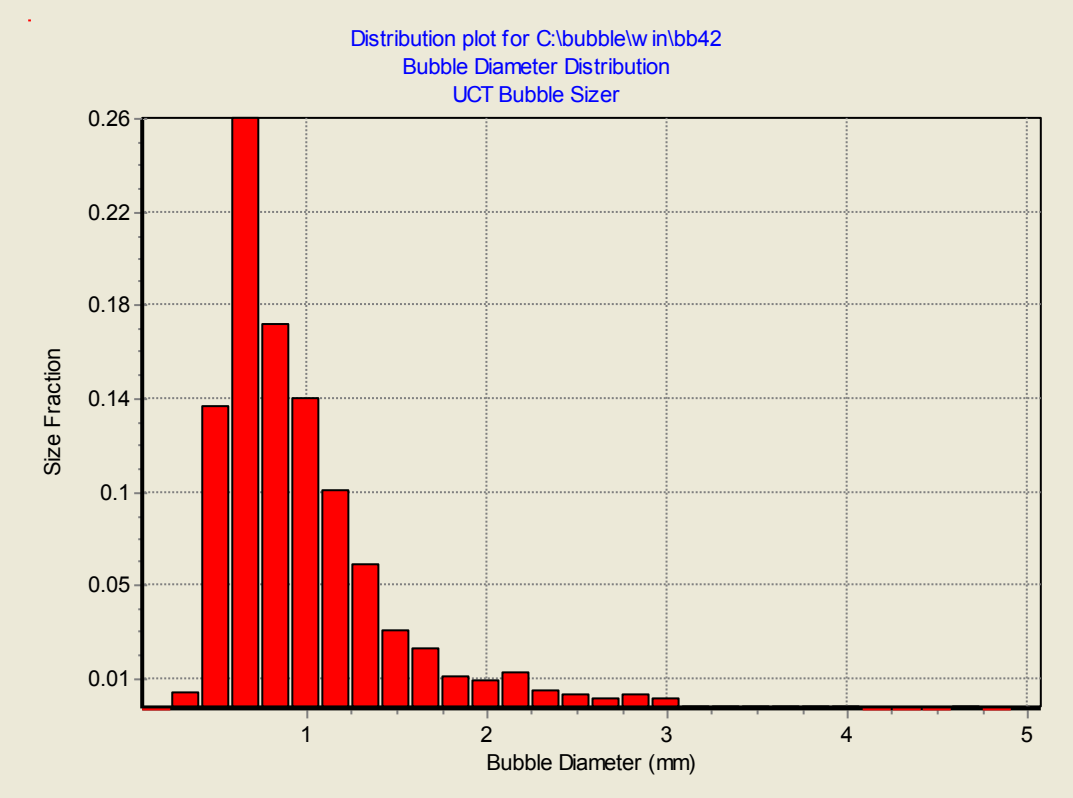

Figure 5.27 Bubble size distributions for MIBC and Dow 250 at a total dosage of 20 ppm

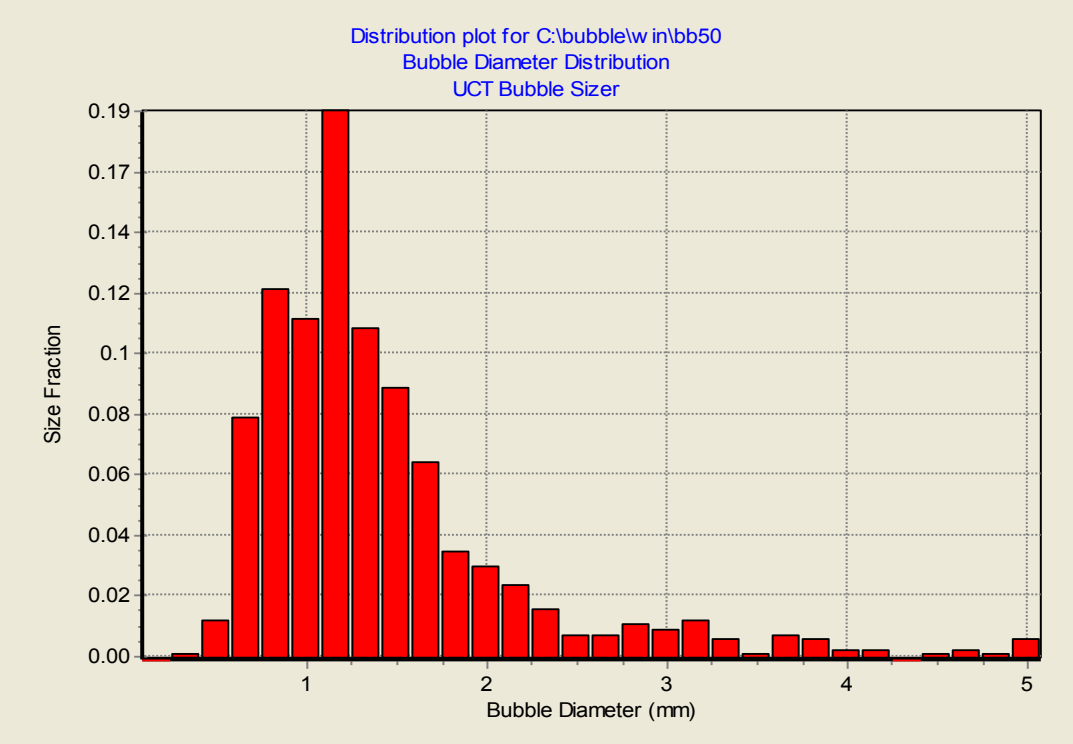

Figure 5.28 Bubble size distributions for MIBC and Dow 250 at a total dosage of 25 ppm

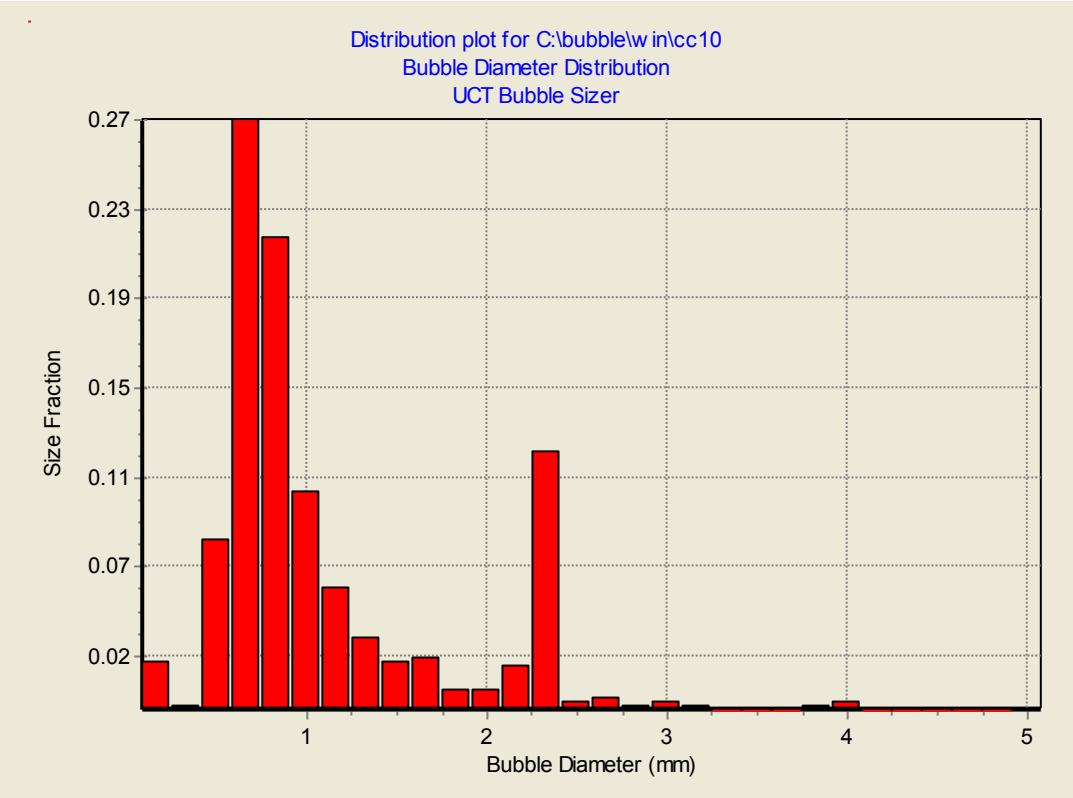

Figure 5.29 Bubble size distributions for 1- hexanol and Dow 250 at a total dosage of 5 ppm

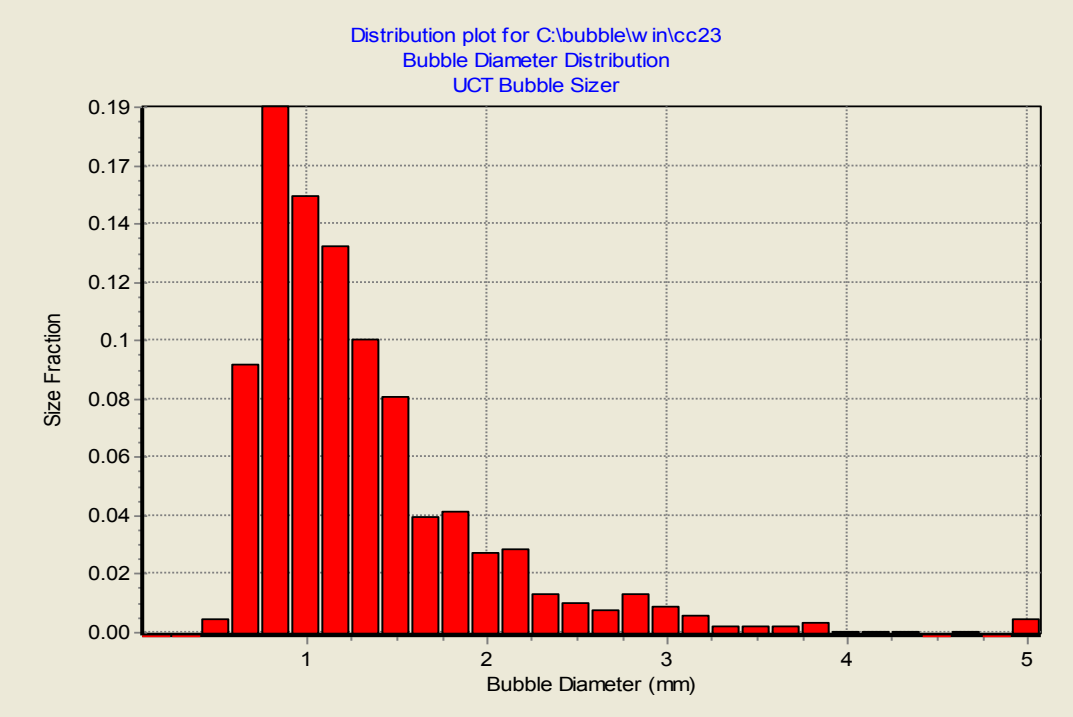

Figure 5.30 Bubble size distributions for 1- hexanol and Dow 250 at a total dosage of 15 ppm

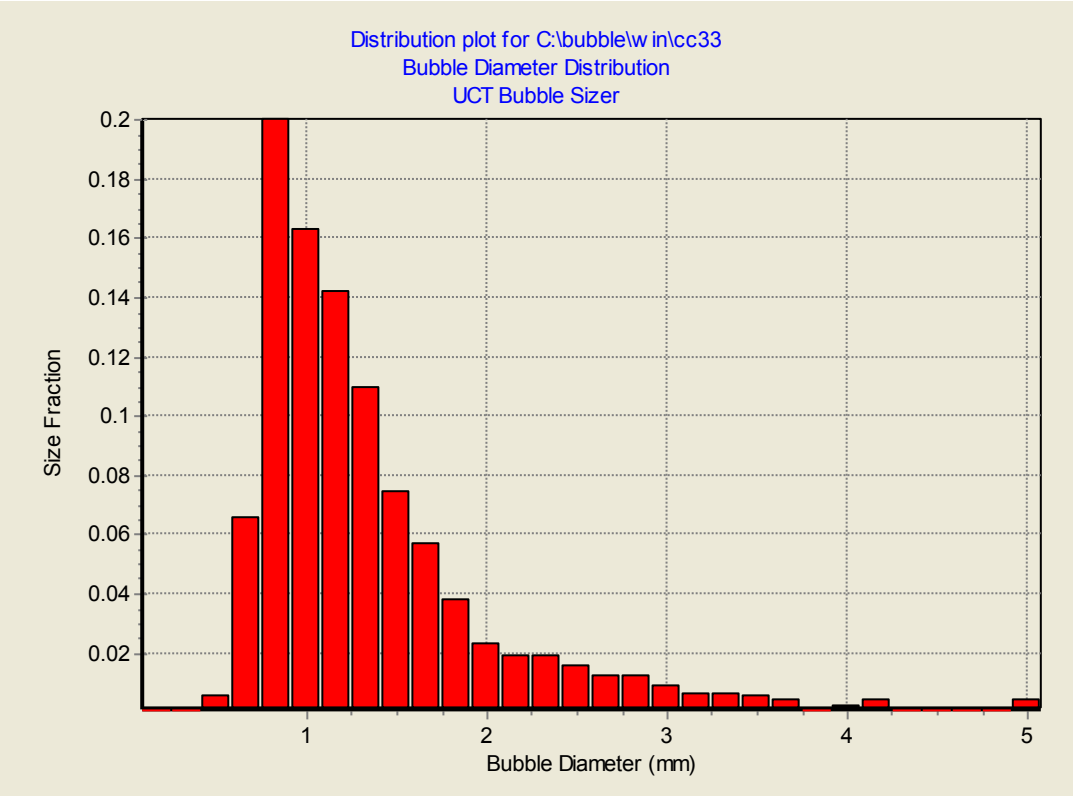

Figure 5.31 Bubble size distributions for 1- hexanol and Dow 250 at a total dosage of 20 ppm

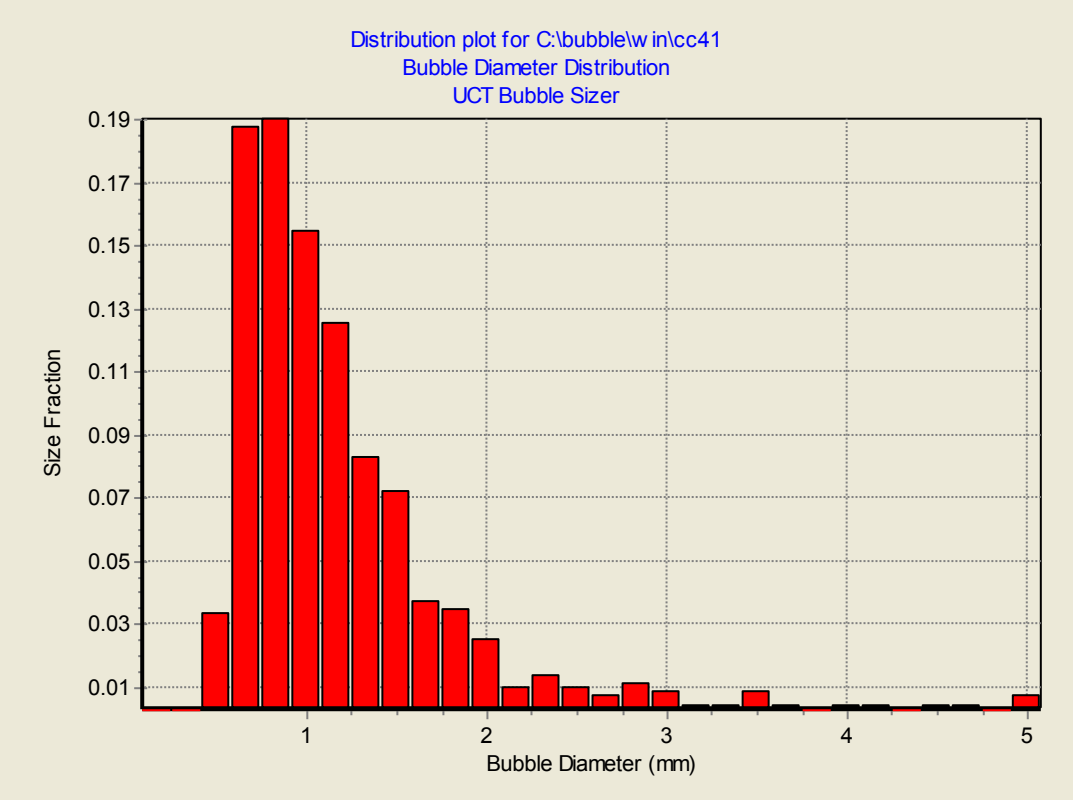

Figure 5.32 Bubble size distributions for 1- hexanol and Dow 250 at a total dosage of 25 ppm

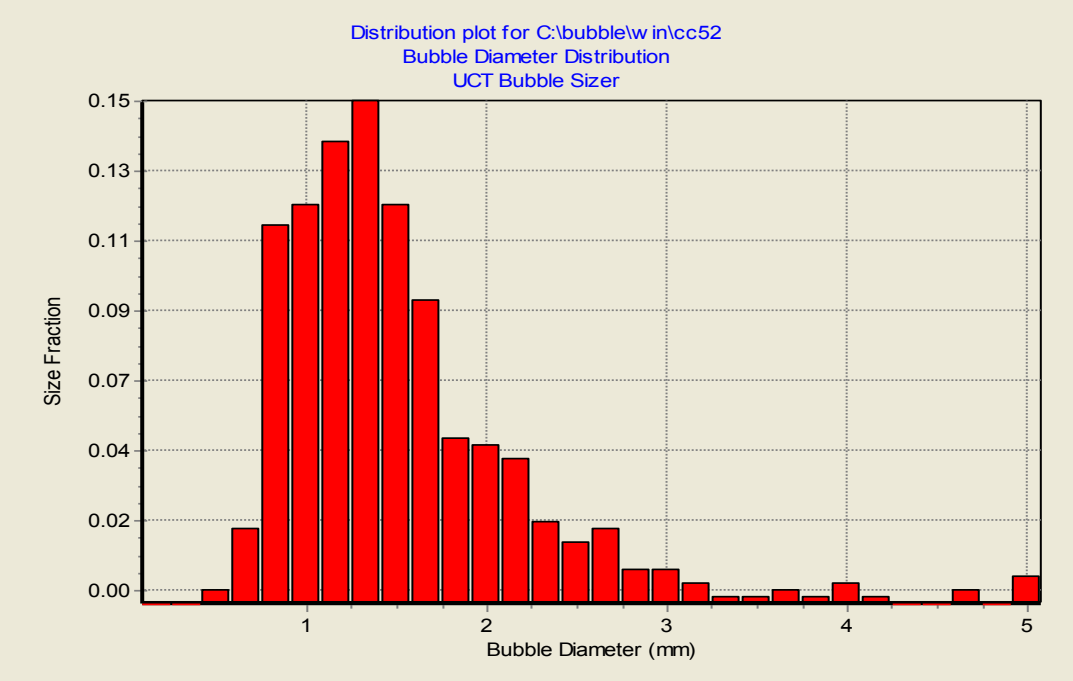

Figure 5.33 Bubble size distributions for 1- hexanol and Dow 250 at a total dosage of 30 ppm

APPENDIX C: EXPERIMENTAL PROCEDURES

C1: Batch Flotation Procedure

Mill ore to 60% passing 75 μm in the presence of collector at 66% solids in synthetic plant water using charge as specified

Transfer to Perspex flotation cell and make up to mark (35% solids) using synthetic plant water

Take feed sample

0 minutes Add depressant

2 minutes Add frother

3 minutes Turn air on and allow froth to develop

5 minutes First concentrate

9 minutes Second concentrate

15 minutes Third concentrate

23 minutes Fourth concentrate

Turn air off

Take tailings sample

Filter all samples (feed, concentrates and tailings)

Dry overnight at 65ºC

C2: Synthetic plant water

Recipe for a 40 litre batch

Chemical Salt	Mass in grams
MgSO4.7H2O	24.6
Mg(NO3).6H2O	4.28
Ca(NO3)2.4H2O	9.44
CaCl2	4.44
NaCl	14.24
Na2CO3	1.2

Add chemical salts to 40 litres of distilled water in the order in which they are listed. Stir well after each addition to ensure that salt is dissolved before subsequent additions.

All salts are chemically pure grade.